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Potential sources of waste heat for heat networks in Scotland

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Executive summary

Aims and findings

This study supports emerging regional and national policies associated with the development and deployment of low-carbon heat networks by examining a variety of potential waste heat sources that have received limited attention in Scotland. Heat networks, or district heating, involves providing heat to homes and businesses via insulated pipes in the form of hot water or steam.

Scotland has committed to achieving net-zero greenhouse gas emissions by 2045. Heat is at the core of Scotland's energy system, accounting for approximately 50% of the energy consumed by homes and businesses, making it the biggest element of Scotland's energy use and its largest source of emissions. The Scottish Government (in line with advice from the Committee on Climate Change) has identified heat networks as one of the 'low-regret' options – low cost and with relatively large benefits - for heat decarbonisation. Its Climate Change Plan 2018[1] (CCP) focuses on significant reductions in emissions from buildings, both residential and non-domestic.

The results of the study can support policymakers and industry in identifying waste heat opportunities, as well as support energy master planning that considers the use of local waste heat sources, thereby enabling both environmental and economic benefits.

The study assesses the waste heat potential of 10 different sectors (distilleries, breweries, bakeries, paper and pulp, laundry, supermarkets, data centres, electricity substations, waste-water treatment plants (WWTP), and landfill) using a variety of data sources and calculation steps (which included excluding significantly small sites, applying assumptions on site activities and energy consumption, etc.). A summary of the waste heat potential is shown in Figure 1.

[1] Climate Change Plan: The Third Report on Proposals and Policies 2008 - 2032

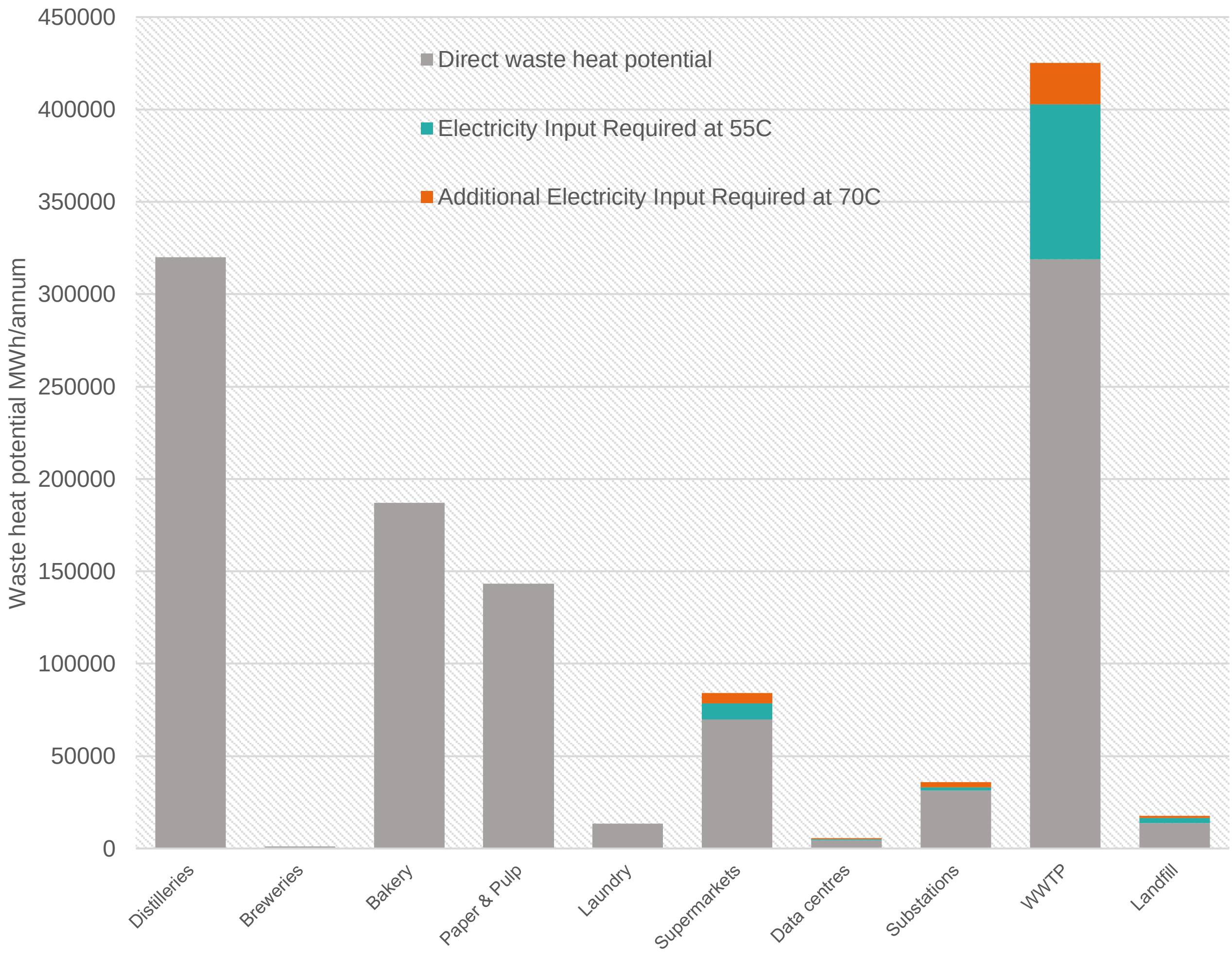

Figure 1: Total waste heat potential per sector and electricity input required for delivery at 55°C and 70°C

Waste heat potential:

- The study has identified a waste heat potential of circa 1,677 GWh across some 932 sites in Scotland. Of these, 699 present low-grade waste heat potential. However, if these low-grade sources are thermally upgraded via an electrically driven heat pump[2], then an increased total waste heat potential of between 1,926 and 1,999 GWh is available. This accounts for approximately 3% of national heat demand (based on the Scottish Government's Heat Map which suggests annual space and water heating demand of circa 60,000 GWh).
- The largest waste heat potential was estimated to be in the distillery and waste-water treatment sectors. Bakeries and paper and pulp are the other sectors with high waste heat potential due to their large energy consumption. Data centres, supermarkets and breweries have relatively lower waste heat potential in comparison to other sectors.

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[2] Calculations reflect the potential electricity required for state-of-the-art heat pump systems when upgrading low grade heat to 55ºC and 70ºC.

A proximity analysis identified:

- 714 waste heat sites (77% of all the sites assessed, presenting a total waste heat potential of 994,112 MWh) have a heat demand greater than 250 MWh within 250m radius of their site.
- 798 waste heat sites (86% of all the sites assessed) have a heat demand of greater than 250 MWh within 500m radius.
- 881 sites (95%) have a heat demand of more than 250 MWh within 1km radius.

District heating opportunities:

- Data centres, breweries, supermarkets, laundries, bakeries and paper and pulp sites have relatively high heat demand in their local areas. As a result, these may provide potential for district heating (DH) opportunities.
- 237 sites (equivalent to 25% of all the waste heat sites we identified, with a total waste heat potential of 146,554 MWh), have an existing DH scheme within 500m.
- Distilleries, laundries, WWTPs, landfills and paper and pulp sites have a relatively low number of sites located within 500m to DH schemes. On the other hand, supermarkets, data centres and bakeries have a relatively high number of sites located within 500m to DH schemes.

Recommendations

- Further investigation is recommended on the technological aspects of waste heat recovery from WWTPs, distilleries and paper and pulp mills, as these sectors have relatively higher theoretical waste heat potential. The potential for waste heat recovery from sewer networks and food manufacturing sites should also be investigated as it was not possible to obtain data or analyse these sources within this project.
- There is a need to review and assess the heat recovery technologies suitable for capturing waste heat from electricity substations. Techno-commercial barriers need to be considered and further assessed.
- The viable distance for the distribution and use of waste heat will vary depending on several factors. Further research in this area and/or reviews of the technical and commercial aspects of recovering and re-using waste heat in district heating systems would be advantageous.
- As only a simplified proximity analysis was undertaken, it would be advantageous to conduct additional analysis to explore the opportunities for supply / demand matching in more detail.

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1 Background

The Scottish Government has set targets to reduce Scotland's greenhouse gas emissions by 75% by 2030, by 90% by 2040 and to achieve net-zero emissions by 2045. Heat is at the core of Scotland's energy system, accounting for approximately 50% of the energy consumed by Scotland's homes and businesses. This makes it the biggest element of Scotland's energy use and its largest source of emissions. The Scottish Government's Climate Change Plan 2018[3] (CCP) focuses on significant reductions in emissions from buildings, both residential and non-domestic. The CCP aims to enable the delivery of secure and affordable energy for Scotland's households, communities, and businesses. In 2020, the Scottish Government introduced the Heat Networks (Scotland) Bill which aims to contribute to Scotland's climate change targets by regulating heat networks in a way which increases investor, supply chain and consumer awareness and acceptance, thereby increasing potential for their deployment. The identification of suitable methods and systems to support the decarbonisation of heat is therefore essential in achieving CCP objectives.

1.1 Objectives

Waste heat sources offer a relatively untapped source of energy that could potentially provide a useful means of low-carbon heat for heat networks. The potential of many valuable sources of usable heat (such as sewage water, electricity substations, etc.) have received limited quantitative analysis in recent years. This research aims to support emerging national and regional policy by examining and mapping key waste heat sources in Scotland to help support policymakers and energy master planners maximise the opportunities for delivering low-carbon heat.

The objectives of the research were as follows:

- To identify potential usable sources of waste and for each source:
- To identify its current / future energy potential
- To identify key characteristics of the waste heat sources
- To develop a GIS map showing the locations of the potential waste heat sources, and
- To identify what proportion of each of the heat sources could potentially be used in district heating networks.

[3] Climate Change Plan: The Third Report on Proposals and Policies 2008 - 2032

3 Methodology

The study applied two different methods to gather data and validate our findings; a literature review and stakeholder engagement. An initial set of potentially suitable waste heat sources were identified before desktop-based research was undertaken to assess their waste heat potential in Scotland. After completing this initial scoping task, key stakeholders were contacted to gather more detailed information on the prioritised waste heat sources and processes. This information was then used to analyse and map each source.

Figure 2 shows the workflow applied to the project.

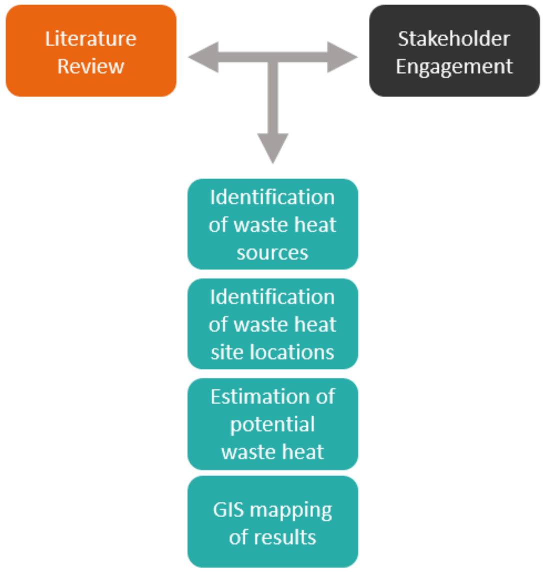

Figure 2: Overview of our approach

1.2 Identification of waste heat sources

The project started with a literature review to identify the major sources of waste heat in Scotland. We identified and reviewed published studies, reports and literature to identify: (i) a set of potentially usable waste heat sources in Scotland, and (ii) yet to be extensively explored sources. Initially, the following potential waste heat sources were considered:

- Industrial processes including the manufacturing of food, drink, chemicals, metal products, rubber, paper and paper products, etc.
- Commercial buildings such as hospitals, data centres, supermarkets
- Landfill sites
- Power stations
- Waste-water treatment works and sewer networks
- Underground train networks
- Mine water

As this project was concerned with identifying and analysing the waste-heat sources that are currently not as well explored in Scotland, we carried out a scoping activity in order to review the above sectors and prioritise them for investigation within the study. The following approach was applied:

- We reviewed the industry-based energy consumption data published by the UK Government Department for Business, Energy and Industrial Strategy (BEIS, 2020) and we shortlisted the most energy-intensive industrial sectors.
- As the (BEIS) sector-level energy consumption data was only available for the whole of the UK and not sub-divided for Scotland, we reviewed the Gross Value Added (GVA) statistics of the energy intensive industries shortlisted above and identified the sectors with greatest contribution to the Scottish economy (The Scottish Government, 2018). Reviewing the GVA statistics allowed us to estimate the potential size of each identified sector in Scotland. In doing so, we applied the assumption that if a sector has a relatively low GVA contribution to Scottish economy, there would be limited opportunity

for waste heat recovery. The study has therefore focused on the investigation of sectors with high GVA contribution to Scottish economy.

- The shortlisted sectors were then subjectively rated (green, amber, red) based on their likely waste heat potential. The ratings drew upon the findings and conclusions from previous waste heat research studies and case studies (McKenna & Norman, 2010), (Jouhara, et al., 2018), (Element Energy, 2015), (BuroHappold Engineering, 2018), (Aalborg University, 2019)), as well as information from the proposed scope of BEIS's Waste Heat Research and National Comprehensive Assessment tender (February 2020).

The waste heat sources presented in Table 1 were identified for further investigation following the completion of the shortlisting process (as outlined in Appendix A). Typical temperature range of each waste heat is shown in the table below.

Table 1: Prioritised waste heat sources

	Sector	Sub-sector	Typical Waste Heat Temperature Range
Industrial Processes	Manufacture of Food Products	Dairy	40ºC – 90ºC
		Bakery	120ºC - 150ºC
		Production of meat products	Unknown
	Manufacture of Beverages	Brewery	120ºC - 150ºC
		Whisky distillery	70ºC - 90ºC
	Manufacture of Paper and Paper products	Paper and pulp mills	>150ºC
	Washing and cleaning of textile and fur products	Industrial laundry sites	80ºC - 120ºC
Commercial	Data processing, hosting and related activities; web portals	Data centres	20ºC – 40ºC
	Retail sale in non-specialised stores with food, beverages or tobacco	Supermarkets	20ºC – 40ºC
Waste Water	Waste-water treatment works	Sewage and waste-water treatment plants (WWTP)	14ºC – 22ºC
	Sewer network	Sewer trunks and sewer pump stations.	14ºC – 22ºC
Electricity	Electricity sub-stations	Supply grid points	40ºC – 70ºC

Landfill	Landfill heat	Inactive landfills – ground source heat	20ºC – 60ºC

1.3 Stakeholder engagement

To gather up-to-date technical and location data on the above sectors we identified and contacted the following stakeholders: Scottish Water Horizons (SWH), Scottish Environment Protection Agency (SEPA), SSE Networks (SSEN), SP Energy Networks (SPEN), Heath Facilities Scotland (HFS), Scottish Assessors Association (SAA). The project calculation and spatial mapping methodology was then suitably adjusted, where necessary, based on the feedback from each stakeholder regarding the availability and the quality of requested datasets.

1.4 Identification of site locations

To calculate the site-specific waste heat potential of the prioritised sectors, we identified a variety of location datasets of interest to the project. Overall, we identified a total of 932 waste heat source site locations. We checked the reliability of these datasets with relevant stakeholders. We also undertook some additional accuracy checks of selected site locations using Google maps and other online resources. The full list of datasets used in this study can be found in Appendix B.

1.5 Estimation of potential waste heat per site

We developed individual methodologies to estimate the waste heat potential of each site considering the unique characteristics and limitations of each heat source. A summary of the methodologies applied are presented in Appendix C.

With an aim to explore the potential waste heat that could be used for district heating, we established two different waste heat source categories based on the average waste heat temperature of each sector. These two categories are: (i) low-grade waste heat sources (<50°C), and (ii) medium-grade waste heat sources (50-150°C).

As shown in the Figure 3 below, low-grade waste heat sources commonly require to be upgraded (e.g. via a heat pump) to increase the temperature to a level that is suitable for district heating. Medium-grade heat sources, on the other hand, offer the potential for direct use due to their relatively higher temperature.

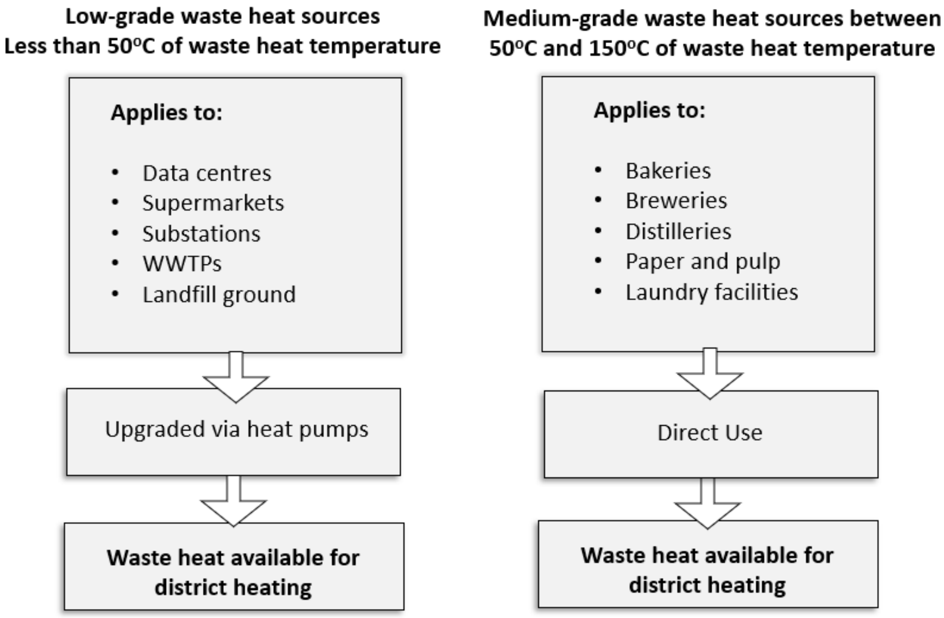

Figure 3: Overview of low and medium grade waste heat sources

3.4.1 Medium-grade heat recovered from industrial processes

Each industrial process consumes different amounts of energy and releases different quantities and qualities of waste heat. To estimate the waste heat released from the different industrial processes (bakeries, distilleries, breweries, bakeries and laundry facilities), we developed a calculation methodology to estimate the thermal energy consumption for each of the sub-sectors (using a set of different assumptions and values per unique sub-sector, see Appendix C. The relevant methodology was then applied to every site before an assessment of '% recoverable' was applied to the gross waste heat estimates. Following the findings from a previous research study, we assumed that half of the sensible heat in an exhaust stream might be technically recoverable (McKenna & Norman, 2010). Due to their relatively high waste heat temperature, we assumed that waste heat could be potentially used at district heating systems without using a heat pump system. This process is presented graphically in Figure 4 below.

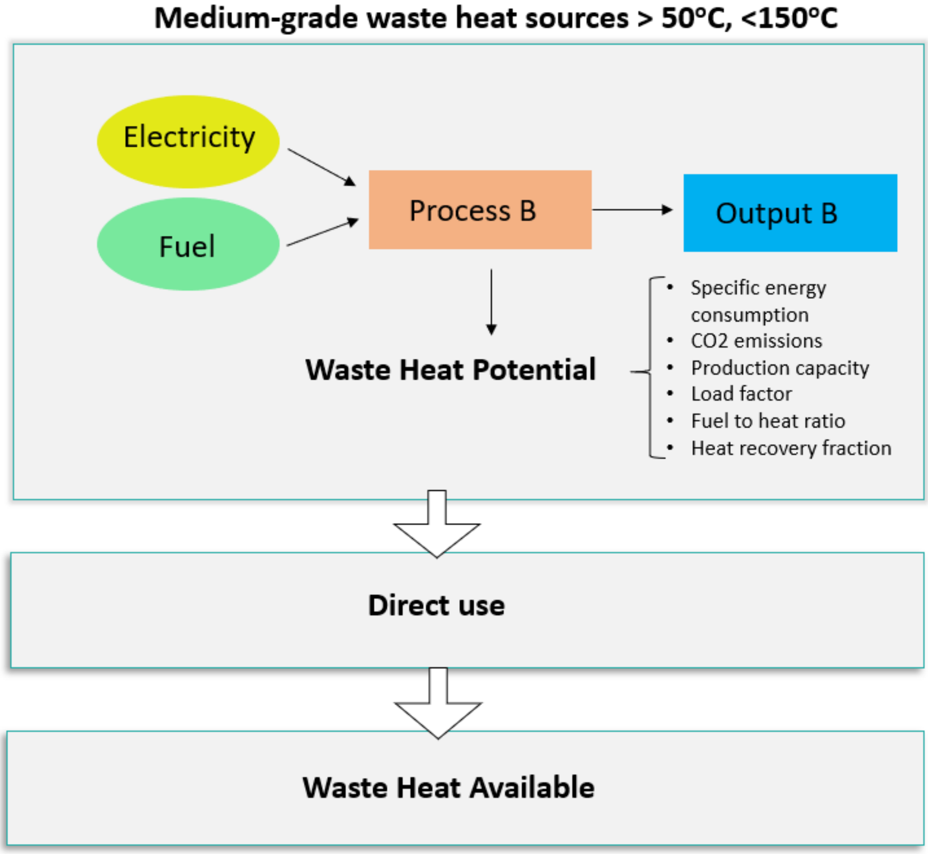

Figure 4: Assessment approach: medium-grade waste heat sources

3.4.2 Low-grade heat recovered from supermarkets, data centres and substations

For the sub-sectors named above, waste heat is typically available from their cooling / refrigeration systems. Cooling and refrigeration systems reject heat in order to reduce the temperature of the refrigerant for re-use in the cooling cycle. The amount and the temperature of the rejected heat depends on the cooling system type. In typical applications, low-grade heat comes from the refrigerant being condensed. In the UK, the temperature of this waste heat is typically between 20°C and 40°C (Carbon Trust, 2020). To assess the waste heat potential of low-grade heat that can be captured from the cooling and refrigerant systems installed at supermarkets, data centres and electricity substations, we estimated the total cooling load and cooling/refrigeration energy consumption of each site. We then applied a standard heat recovery ratio to each site. Further details can be found in Appendix C.

As the heat that can be captured from cooling and refrigeration systems is likely to be less than 50°C, we carried out a simple heat pump analysis and estimated the amount of useful heat energy that could be available based on two upgrade scenarios i.e. an output temperature of 55°C and 70°C. These temperatures were chosen to highlight the difference in (end-use) energy potential of these waste heat sources supplying common “3rd generation” district heating systems (at circa 70°C) versus future “4th generation” systems (at circa 55°C) which can operate at lower temperatures. This process is presented graphically in Figure 5 below.

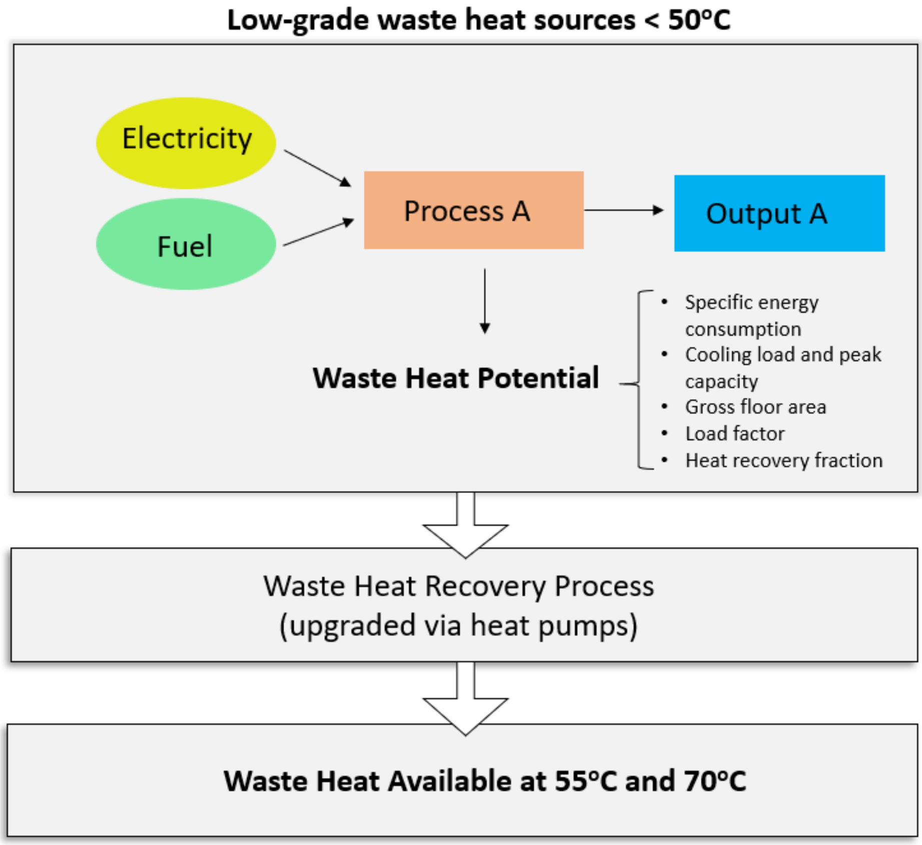

Figure 5: Assessment approach: low-grade waste heat sources (supermarkets, data centres, substations)

3.4.3 Low-grade heat recovered from Waste-Water Treatment Plants:

At WWTPs, treated waste water is commonly available in large quantities and continuously, thus providing a good opportunity for recovering low-grade heat. To quantify the total amount of waste that could potentially be captured from WWTPs, we firstly identified the waste-water treatment plants located in Scotland and assessed their site-specific effluent rates and average effluent temperatures (using sample data obtained from Scottish Water Horizons). Then, using average waste-water volume figures, we estimated the potential waste heat available at each WWTP. Thereafter, we carried out a simple heat pump analysis and calculated the useful heat energy that available based on the same two heat pump upgrade scenarios (55ºC and 70ºC) as outlined previously. Our general approach for heat recovery from waste-water treatment works is shown in Figure 6.

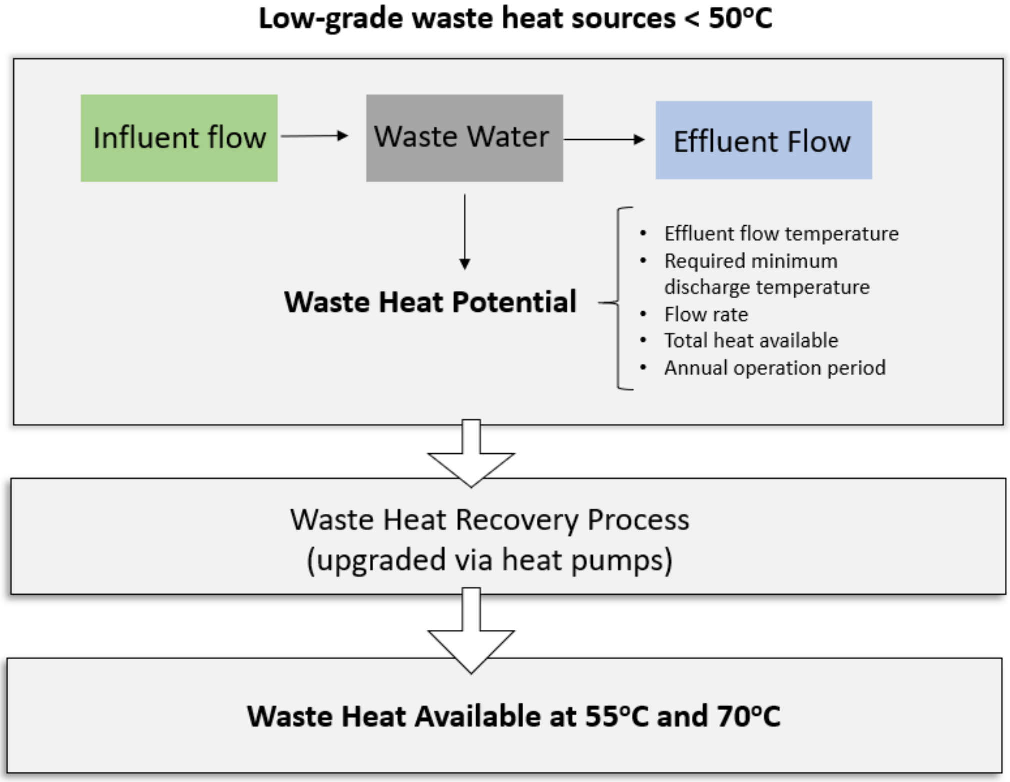

Figure 6: Assessment approach: Low-grade waste heat source (WWTP)

3.4.4 Low-grade heat recovered from landfill

A previous research study shows that the principles of geothermal heating systems can be applied to landfill sites in order to recover low-grade heat, and that such landfill based shallow geothermal systems can be more efficient than typical ground-based systems, as ambient temperatures in landfills can be warmer than standard ground by 10°C to 45°C (Grillo, 2014).

To estimate the waste heat potential of inactive landfills, we estimated landfill site area (from information published by SEPA) and thereafter applied a calculation that used assumptions regarding a ground temperature and heat pump capacity. Due to lack of information available on landfill sizes, we were not able to calculate the site-specific waste heat potential of each inactive landfill. We assumed a ground temperature of 21°C and that a standard ground source heat pump system (with a capacity of 73 kW – based on a pilot study tested and demonstrated in Ireland) would be applicable to all the inactive landfills we identified in this study.

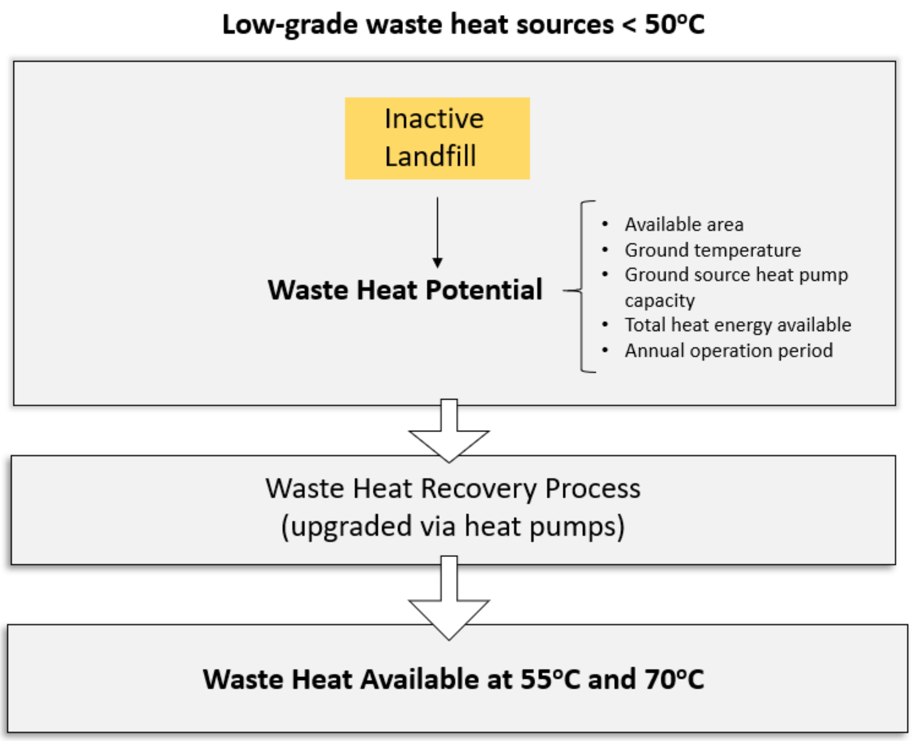

Figure 7: Assessment approach: Low-grade waste heat source (Landfills)

1.6 Waste heat available at 55°C and 70°C

With the aim of assessing the total amount of waste heat that could be available for district heating, we estimated the waste heat potential considering two different delivery temperatures: 55°C and 70°C. Therefore, for the low-grade waste sources, we carried out a simplified heat pump analysis and assigned a theoretical Coefficient of Performance (COP) for each waste heat source using the equations below:

$$COP_{HP,Theoretical\ Max} = \frac{T_{Hot}\ (K)}{T_{Hot}(K) - T_{Cold}(K)}$$

$$COP_{HP} = System\ efficiency \times COP_{HP,Theoretical\ Max}$$

Table 2 shows the estimated COPs we used in this study. As noted earlier, the industrial processes (such as bakeries, distilleries, etc.) with medium-grade waste heat potential were not included in this analysis.

Table 2: Low-grade waste heat sources and theoretical COP

Sector	Source of Waste Heat	Typical waste heat temperature	COP_{HP} @ 55ºC	COP_{HP} @ 70ºC
Commercial	Data centre cooling systems	35ºC	8.2	4.9
	Supermarket cooling and refrigerant systems	35ºC	8.2	4.9
Waste water	Waste-water treatment works	12.3ºC	3.8	3.0
Electricity	Electricity substations	45ºC	16.4	6.9
Landfill	Inactive landfills (ground source)	21ºC	4.8	3.5

Figure 8 below shows the theoretical heat pump COP values at condenser (i.e. output) temperatures of 55ºC and 70ºC, considering an average waste heat temperature. It must be noted that actual heat pump COP will vary depending on product-based characteristics, system capacity and external conditions. Therefore, these values only provide a high-level indication of potential COP values that could be achieved at different waste heat temperatures.

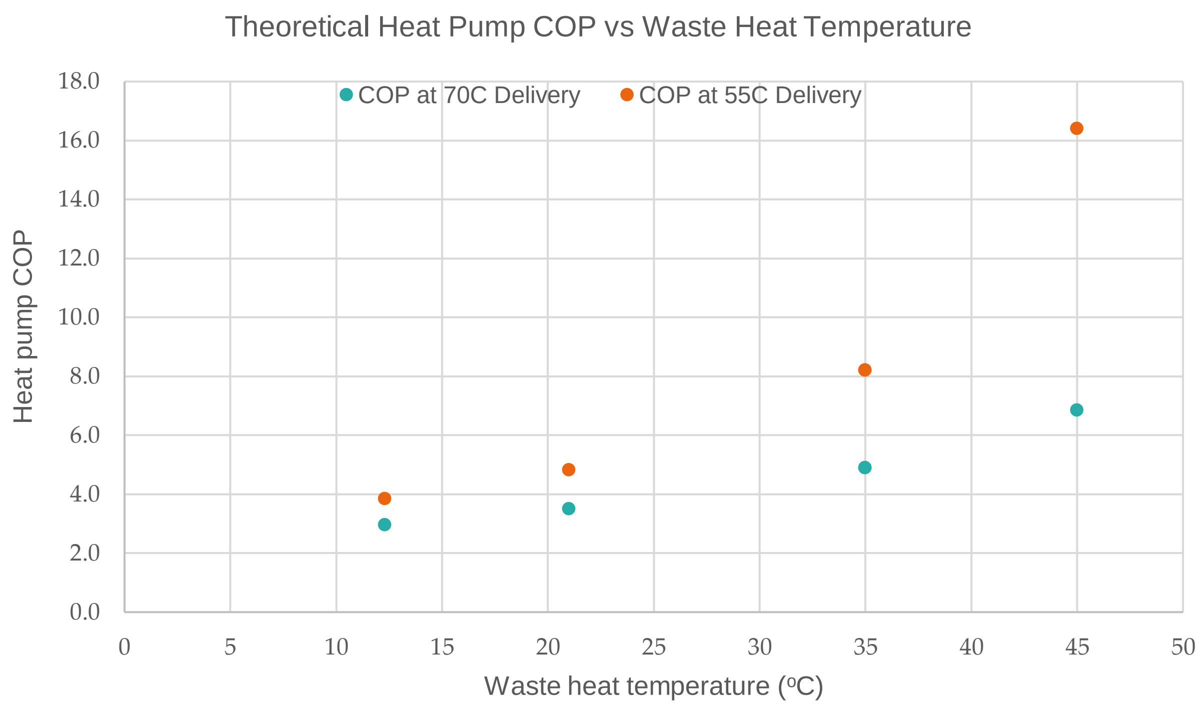

Figure 8: Theoretical heat pump COP vs waste heat temperature

By applying the theoretical COP values, we estimated the upgraded waste heat potential of low-grade heat sources (Figure 8). Results and seasonal variation details can be found in Section 4.

1.7 Limitations

There were limitations with the methodology:

Data quality - The quality of datasets used in this study significantly varies. For example, information such as the site-specific production capacity and energy consumption of sub-sectors such as breweries, bakeries and laundries, was not readily available (Table 3). As a result, several assumptions had to be made.

Table 3: Data quality and completeness per sector

Sector	Quality and completeness of the location datasets	Quality and completeness of the technical datasets
Distilleries	**Good**	**Good**
Breweries	**Poor**	**Average**
Bakery	**Good**	**Poor**
Paper & Pulp	**Good**	**Good**
Laundry	**Good**	**Poor**
Supermarkets	**Good**	**Average**
Data centres	**Poor**	**Average**
Substations	**Average**	**Poor**
WWTP	**Good**	**Good**
Landfill	**Good**	**Poor**

Detailed information on the methodologies can be found in Appendix C.

Lack of available information on data centre locations – In this study, we identified nine commercial data centres located in Scotland, although we expect the actual number to be much higher. In addition, the locations of some commercial data centres are likely to be kept confidential for security reasons. The total waste heat that can be recovered from data centres is therefore likely to have been underestimated in this study.

Heat recovery processes –The technical feasibility of heat recovery processes was not assessed in detail, as this was out with the project scope. The amount of waste heat available for district heating systems is likely to vary depending on a range of site-specific technical factors relating to various heat recovery processes.

Variation in waste heat temperature – To estimate the waste heat potential of each site, we used an average waste heat temperature for each heat source (see Table 1). Due to limited information being available on actual waste heat temperatures we have applied theoretical values that align with previous research studies. Waste-water treatment was the only sector where we used temperature data that had been obtained from site-based monitoring (i.e. waste heat temperature and flow rates as obtained from Scottish Water Horizons).

Proximity of waste heat sources to district heating networks – There is limited information available regarding typically distances from which a waste heat source could successfully (techno-economically) be connected to a nearby district heating system. The connection distance depends heavily upon site-specific constraints, the nature of the waste heat supply, relevant heat recovery technologies and also upon economic and regulatory requirements. In this study, we used indicative distances to identify waste heat sources that are in relatively close proximity to district heating networks and to areas heat demand. Detailed site-specific studies need to be carried out in order to assess actual feasibility.

Limited information on transformer types – The amount of waste heat that can be captured from electricity substations varies depending on the cooling system type. Previous research highlights that Oil Forced Water Forced (OFWF) transformers typically offer the greatest opportunity for heat recovery (Imperial College London and Sohn Associates (2014)). In this study we were not able to identify the types of individual substations due to lack of publicly available information. To avoid overestimating the waste heat potential of substations, we followed a conservative approach and assumed that only 1% of peak load capacity would be recovered.

2 Results

This section presents the waste heat potential of each sector and upgraded waste heat potential of low-grade waste heat sources as well as an overview of the findings of heat demand proximity analysis.

2.1 Waste heat potential

The study has identified a total of 932 waste heat sites in Scotland. This comprises:

- 233 medium-grade waste heat sites (50-150ºC) (presenting an estimated direct use energy potential of 665 GWh); and
- 699 low-grade waste heat sites (<50ºC) (presenting an estimated energy potential of 438 GWh (direct, <50ºC), 536 GWh (upgraded via heat pump to 55ºC, requiring an electricity input of 98 GWh) and 568 GWh (upgraded via a heat pump to 70ºC, requiring an electricity input of 130 GWh).

Table 4 below provides a summary of the waste heat potential per sub-sector.

Table 4: Potential waste heat available per sector

<table>
<tr><th></th><th>Sector</th><th>No. Sites</th><th>Total Waste Heat Potential (MWh)</th><th>Average Potential per Site (MWh)</th><th></th><th>Total Potential Heat at 55ºC (MWh)</th><th>Total Electricity Input Required (MWh)</th><th></th><th>Total Potential Heat at 70ºC (MWh)</th><th>Total Electricity Input Required (MWh)</th></tr>
<tr><td rowspan="5">Medium-grade sources</td><td>Distilleries</td><td>129</td><td>320,104</td><td>2,481</td><td rowspan="6"></td><td colspan="2" rowspan="5">As noted.</td><td rowspan="6"></td><td colspan="2" rowspan="5">As noted.</td></tr>
<tr><td>Breweries</td><td>15</td><td>992</td><td>17</td></tr>
<tr><td>Bakery</td><td>73</td><td>187,040</td><td>2,562</td></tr>
<tr><td>Paper & Pulp</td><td>6</td><td>143,405</td><td>23,901</td></tr>
<tr><td>Laundry</td><td>10</td><td>13,341</td><td>1,631</td></tr>
<tr><td>Low-</td><td>Supermarkets</td><td>431</td><td>69,889</td><td>162</td><td>78,412</td><td>8,523</td><td>84,152</td><td>14,263</td></tr>
</table>

	Data centres	9	4,546	505		5,101	554		5,474	928
	Substations	55	31,306	569		33,215	1,909		35,843	4,537
	WWTP	24	318,905	13,287		402,828	83,922		425,207	106,302
	Landfill	180	13,680	76		16,530	2,850		17,589	3,909
	Total:	932	1,677,238			1,926,058	97,759		1,998,520	129.938

The largest waste heat potential was estimated to be in the distillery and waste-water treatment sectors. With the implementation of suitable heat recovery methods (i.e. water-to-water heat pumps), significant amounts of heat can be re-used. Bakeries and paper and pulp are the other sectors with high waste heat potential due to their large energy consumption. Data centres, supermarkets and breweries have relatively low waste heat potential in comparison to other sectors as shown in the figures below.

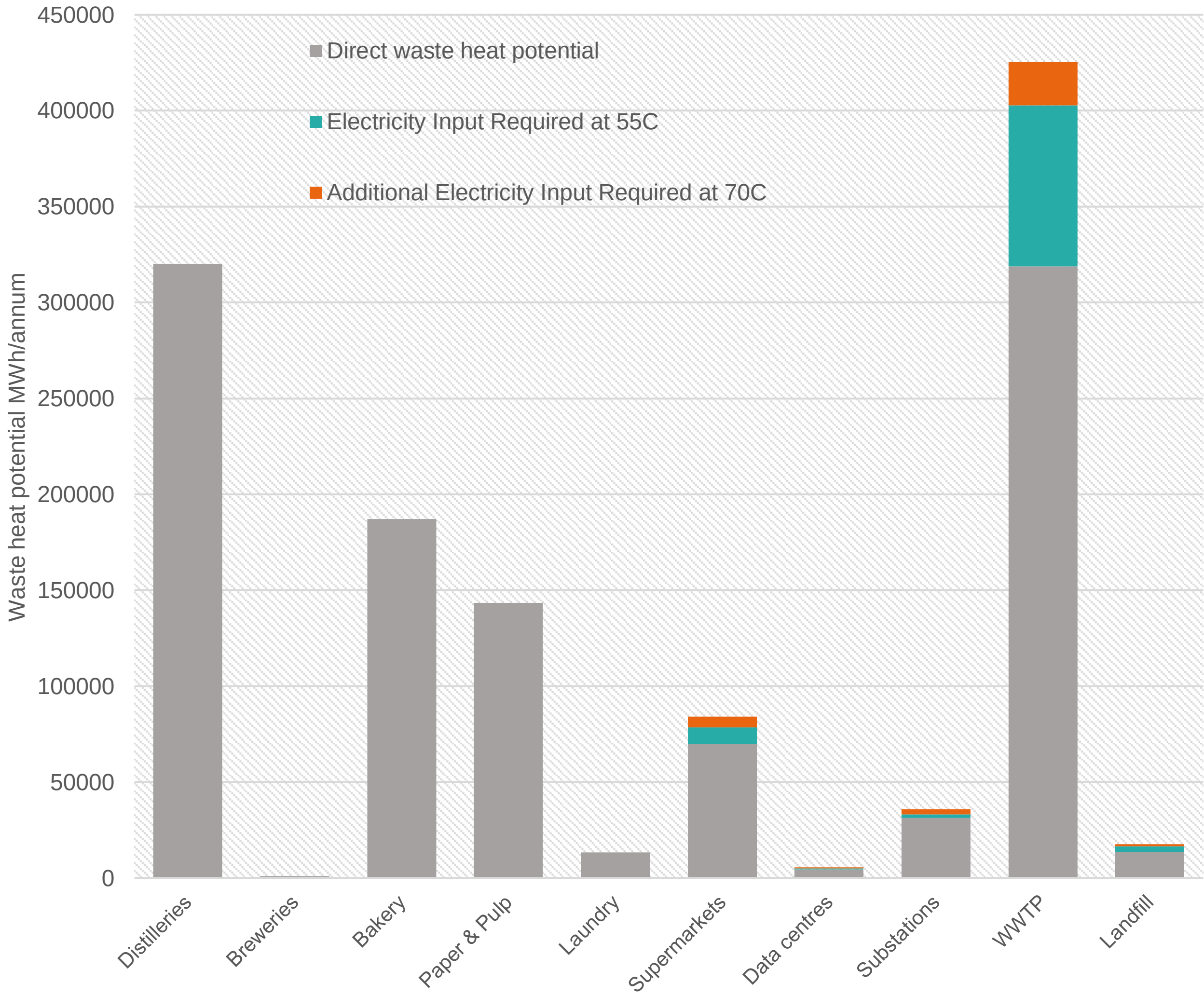

Figure 9: Total waste heat potential per sector and electricity input required for delivery at 55°C and 70°C

4.1.1 Distribution of waste heat potential per sector

As shown in the data distribution bars in Figure 10, the heat recovery potential of distilleries and bakeries vary significantly. This is due to the significant difference in their annual production capacities. Whereas, the distribution of waste heat potential of breweries and landfills are relatively low in our data set as we applied a set of standard assumptions due to the availability limited amount of site-based technical data.

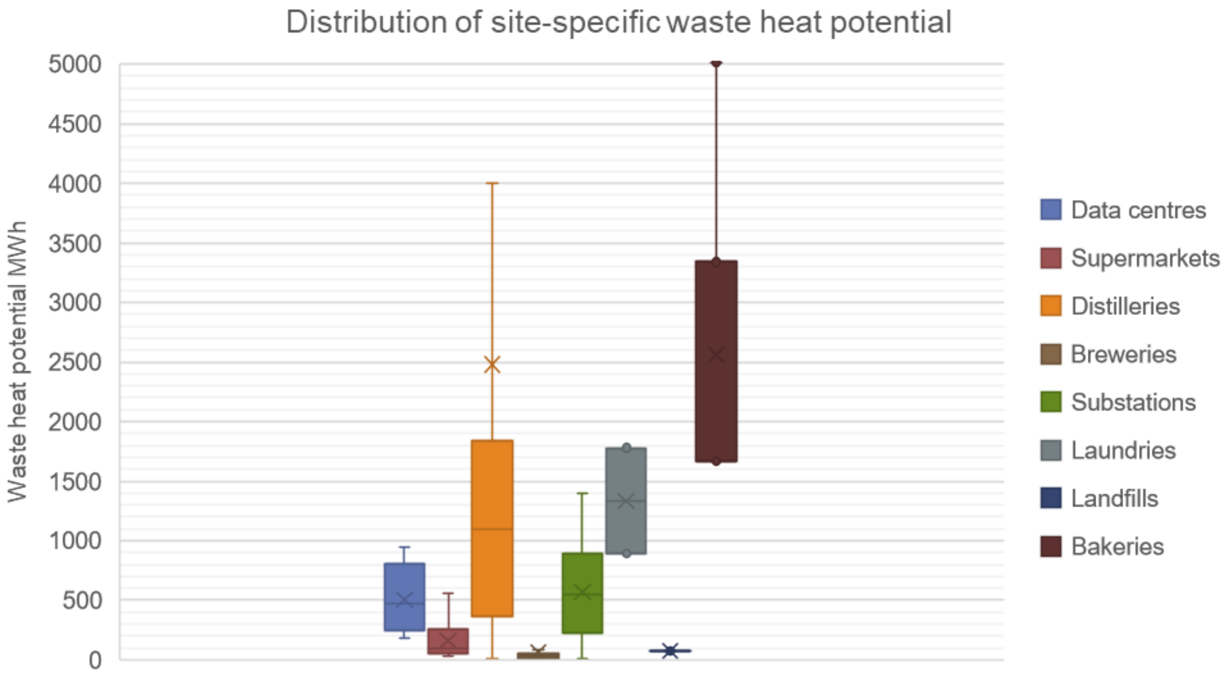

Figure 10: Distribution[4] of waste heat potential per sector – low average potential

Both paper and pulp and waste treatment works have very high waste heat potential in comparison to other sectors. As shown in Figure 11 below, both sectors have a high variation in waste potential.

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[4] **The graph shows a Box and Whisker distribution. The upper and lower lines of the whisker represent the maximum and minimum values of the data being analysed. The upper and lower lines of box represent the 3rd and 1st quartile of the data range being analysed, respectively. The 'X' on the plots denotes the mean value of the data being analysed.**

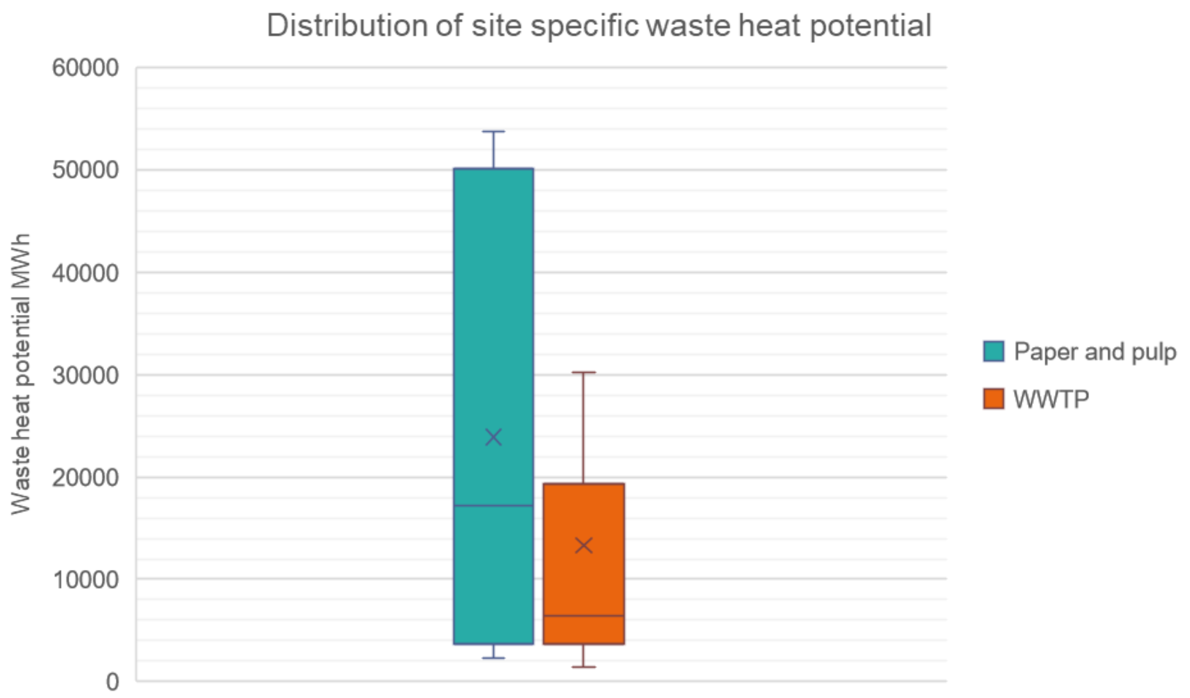

Figure 10: Distribution of waste heat potential per sector - high average potential

2.2 GIS spatial mapping analysis

A single dataset of site details and waste heat potential was compiled from the sources outlined above. For each datapoint the following details have been created:

- Sector – bakery, distillery, brewery, supermarket, data centre, WWTP, landfill, paper & pulp, laundry, substation
- Name of the waste heat entity
- Address, town and post code
- Easting and Northing
- Use of waste heat potential – upgraded or direct use
- Waste heat potential (MWh)
- Upgraded waste heat potential (55°C) MWh
- Upgraded waste heat potential (70°C) MWh
- Heat recovery medium – air, water, oil etc.
- Temperature range
- Seasonal variation – low, medium, high

The dataset was subsequently imported into QGIS (a free and open-source desktop GIS application) as a Delimited Text Layer (.csv) and displayed as points using the Easting and Northing details as derived from each site's post code. A base map layer (OpenStreetMap) and a Scotland boundary was added. The Coordinate Reference System 'OSGB 1936 / British National Grid' was used throughout to ensure consistency and accuracy of the data presented and the results yielded. The imported point data was initially categorised by *Sector*, see Figure 12. Most sites are aggregated in major conurbations including Glasgow, Edinburgh, Dundee and Aberdeen. Supermarkets are the most prevalent with 432 sites plotted (green markers).

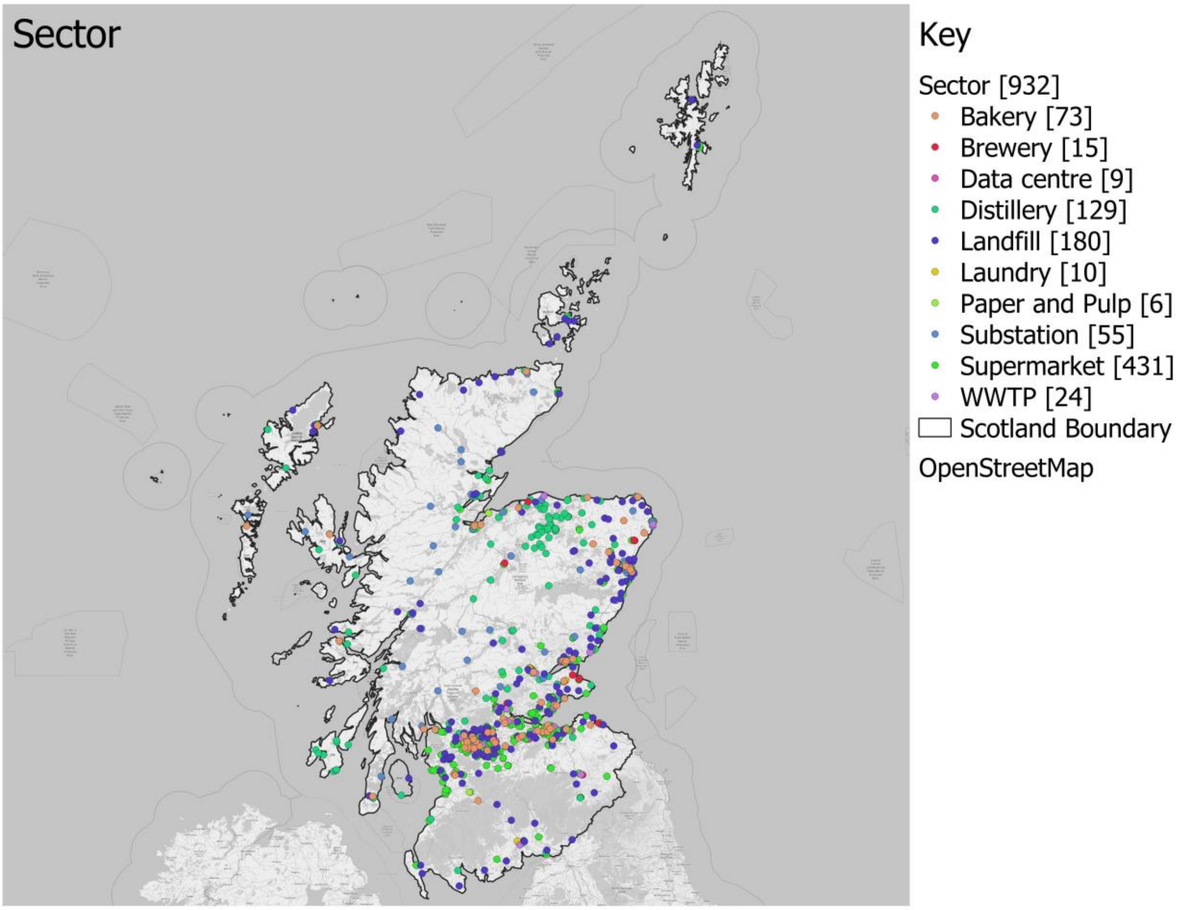

Figure 11: GIS view of all sites (number of sites in square brackets)

When the point data were sorted by *Waste Heat Potential (MWh/yr)*, and graduated in colour (so that the darker colours show increasing potential for waste heat (and vice versa)), (see Figure 13 below) the sites with waste heat potential 50-500MWh/yr are most prevalent.

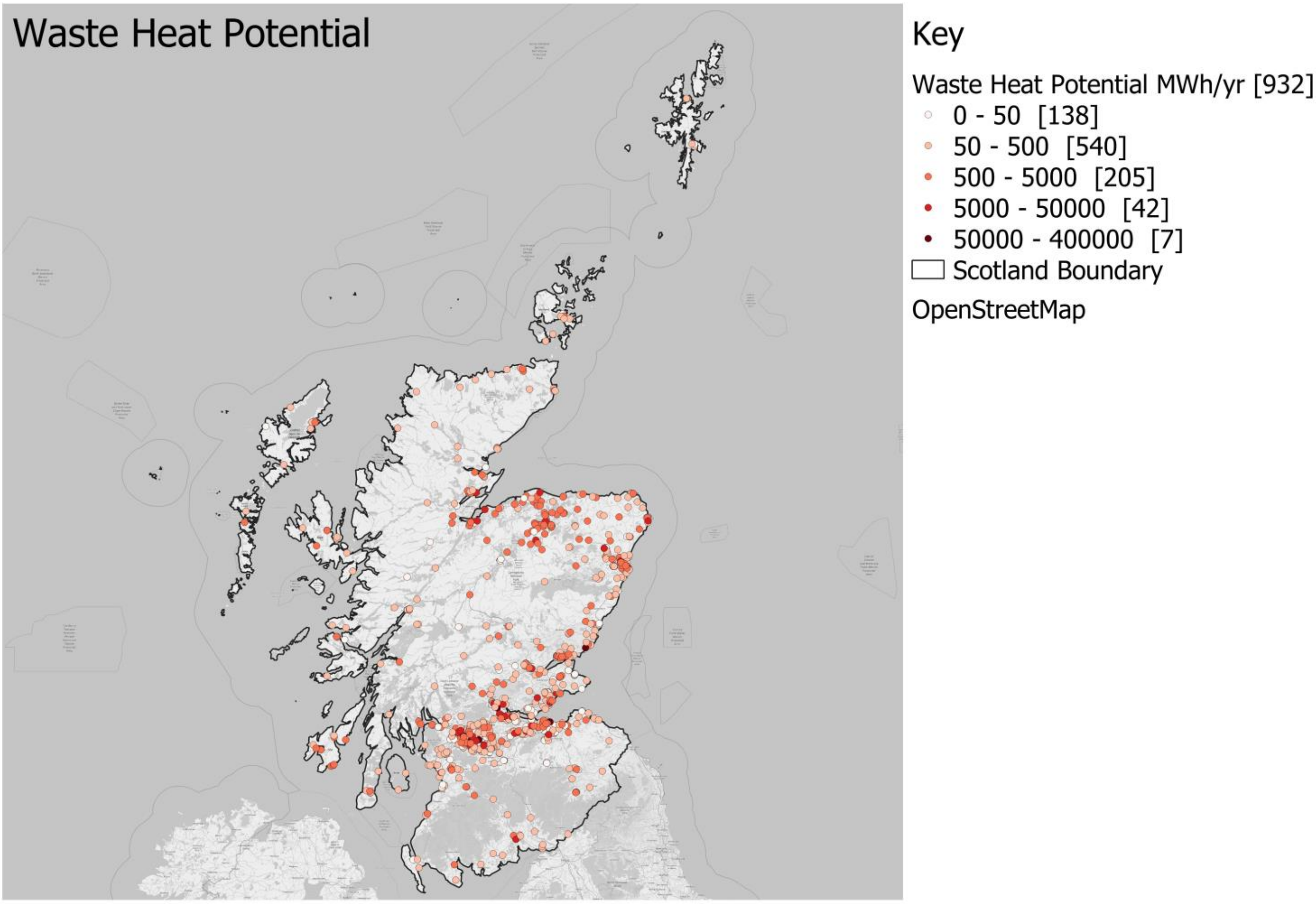

Figure 12: GIS view of waste heat potential distribution (number of sites in square brackets)

Figure 14 below shows sites from Figure 13 albeit presented as a waste heat density map.

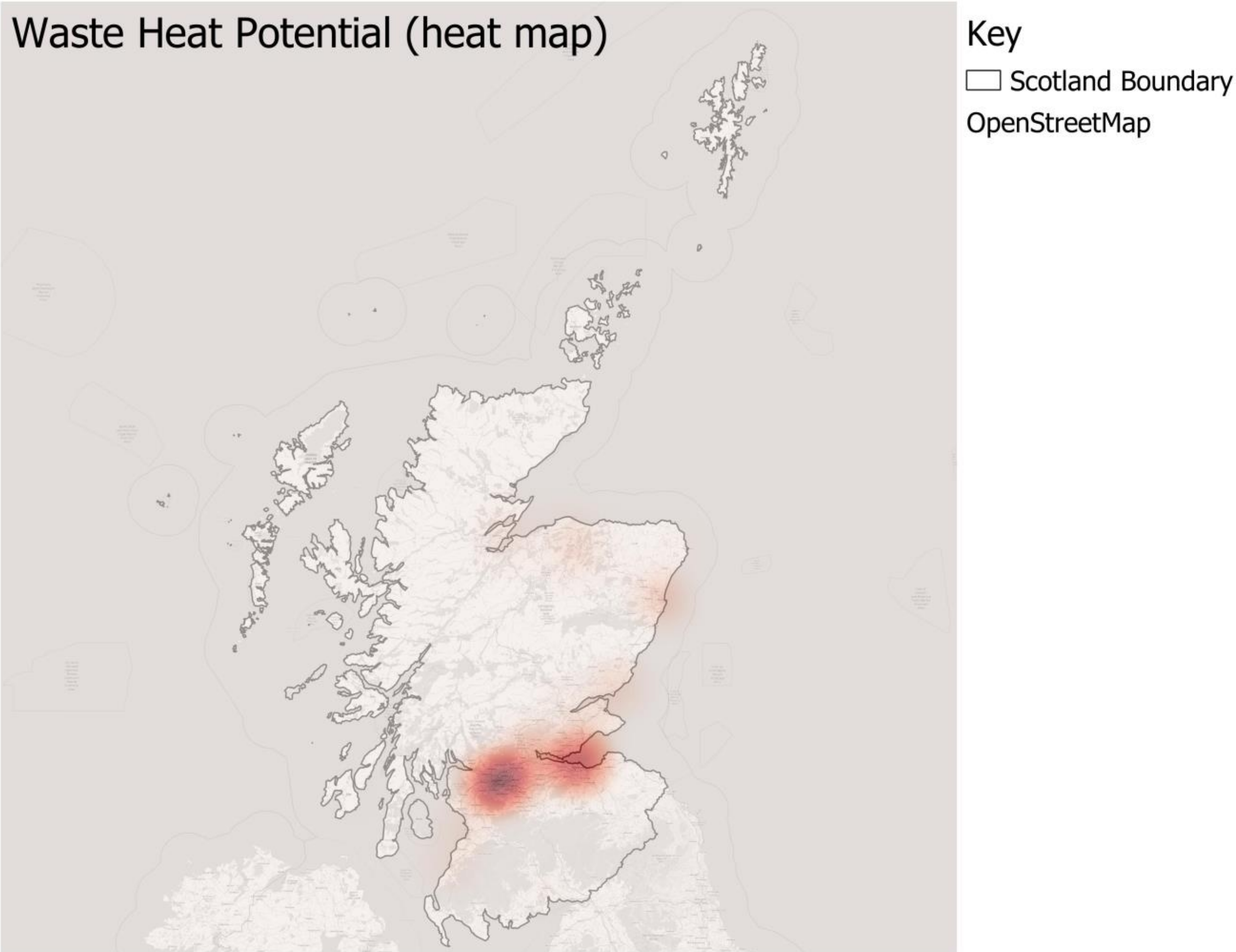

Figure 13: GIS view of waste heat density

When the point data was sorted by *Temperature Range (°C)* and graduated in colour so that darker colours represent higher temperatures (and vice versa) (see Figure 15 below) the sites with lowest temperature range (i.e. <40°C) account for ~70% of sites. There are 139 sites with temperature range 80-120°C and many of these are distilleries in Speyside and the Islands.

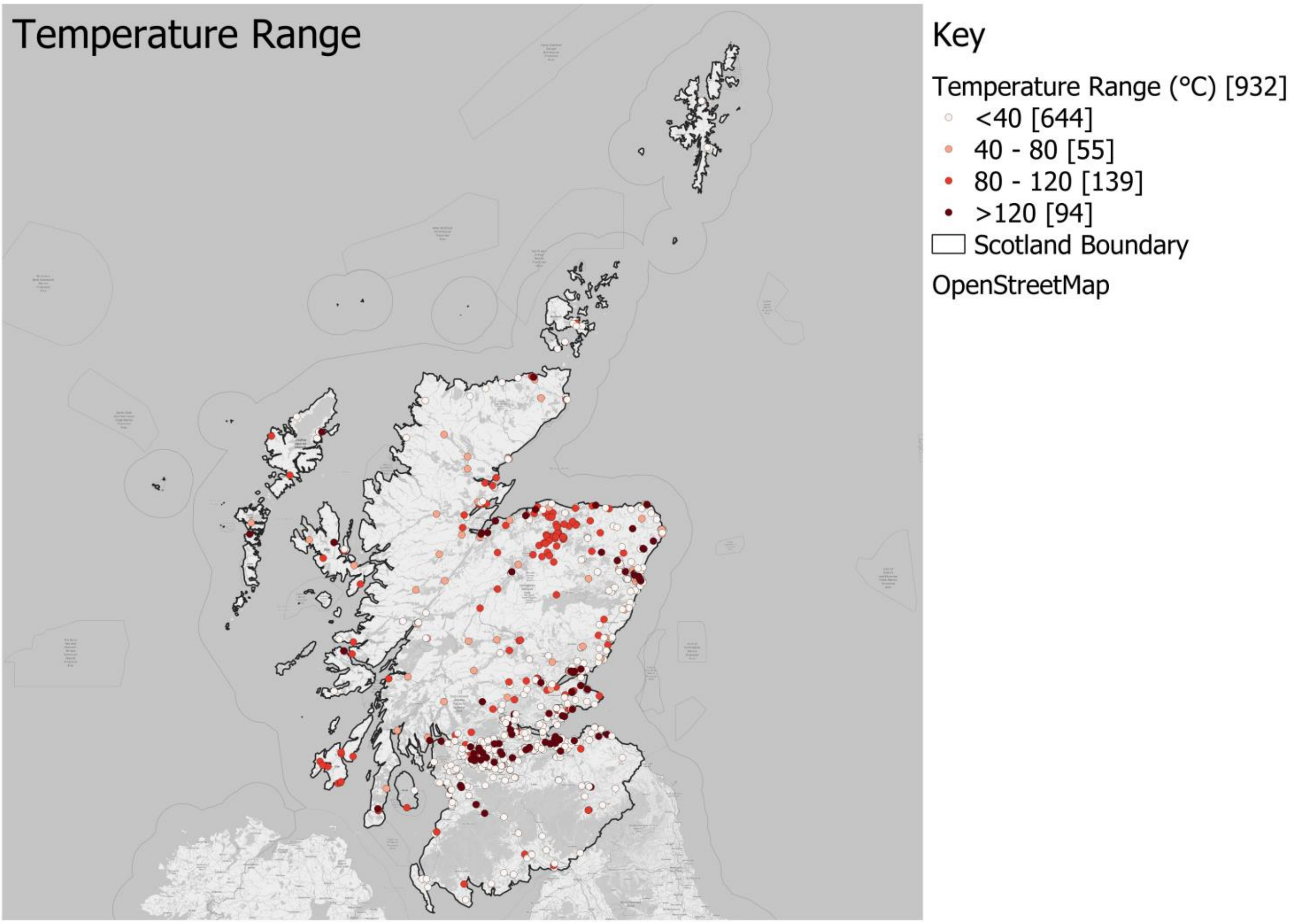

Figure 14: GIS view of waste heat sources based on temperature range (number of sites in square brackets)

2.3 Proximity analysis

In this study, we assessed and mapped the proximity of (1) individual waste heat sources to existing heat demand points in Scotland and (2) individual waste heat sources to existing DH schemes. The moving / distribution of waste heat from a supply point to a point of use with high heat demand can be complicated and require careful consideration of site-specific constraints and technical-economic viability. The viable distance for the transport of waste heat will vary depending on several factors including its temperature and flowrate (i.e. energy quantity and quality), the temperature difference / gradient between the waste heat and the heat network and the supply and demand profiles.

Whilst a site-specific feasibility study would typically be required to accurately assess the potential viability of recovering and utilising waste heat, within this study we have undertaken a generalised proximity analysis to assess the level of heat demand in relatively close proximity to each waste heat site plus analysis of the supply and demand levels. We have carried out this analysis based on three different radii from the waste heat sites: 0.25km, 0.5km and 1km. It should be noted that there is limited research on the topic of viable distances for recovering waste heat for district heating; this is understandable given the site-specific considerations that affect viability.

4.3.1 Proximity to existing heat demand

Scottish Government provided access to spatial data[5] which included heat demand values for Scotland. The values are associated with every property in Scotland that has a Unique Property Reference Number (UPRN) and the heat demand is based on estimates or actual energy billing data, where this is available. The data were available aggregated at different spatial resolutions. The highest resolution, 50x50m grid size, data was downloaded and imported into the map of waste heat sources. The energy demand 'bandings' (and the colours used to represent them) were re-created (see Figure 16 below) to match those used within the publicly accessible Heat Map.

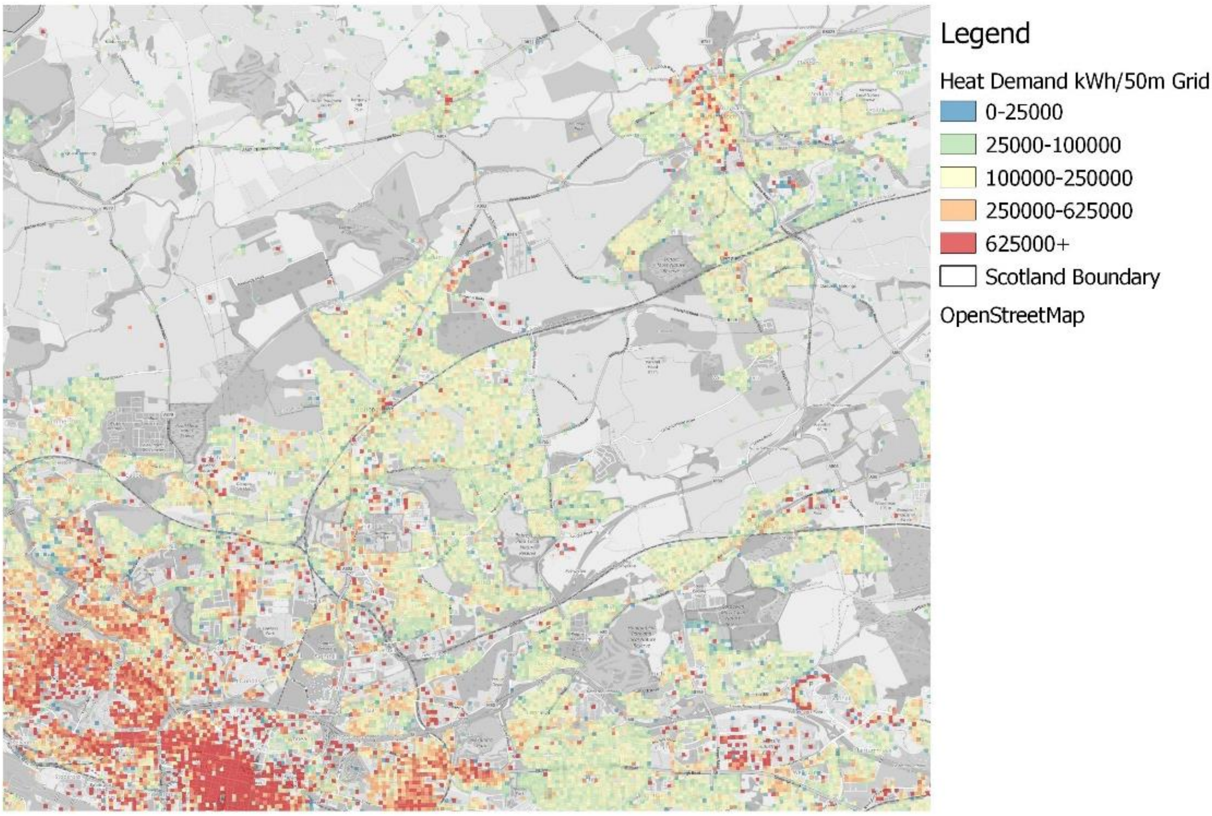

Figure 15: Example of the mapped heat demand data

Waste heat site locations, together with the heat demand data, were used to determine the potential/ theoretical heat demand within a set distance from each site. Buffer zones of 250m, 500m and 1000m from each site were created (shown as green, amber, red respectively in Figure 17 below).

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[5] The underpinning data are based on data derived from: 3.2M addresses, 2.9M Scottish Assessor records, 0.8M Energy Performance Certificates and over 20,000 public sector properties with actual energy billing data.

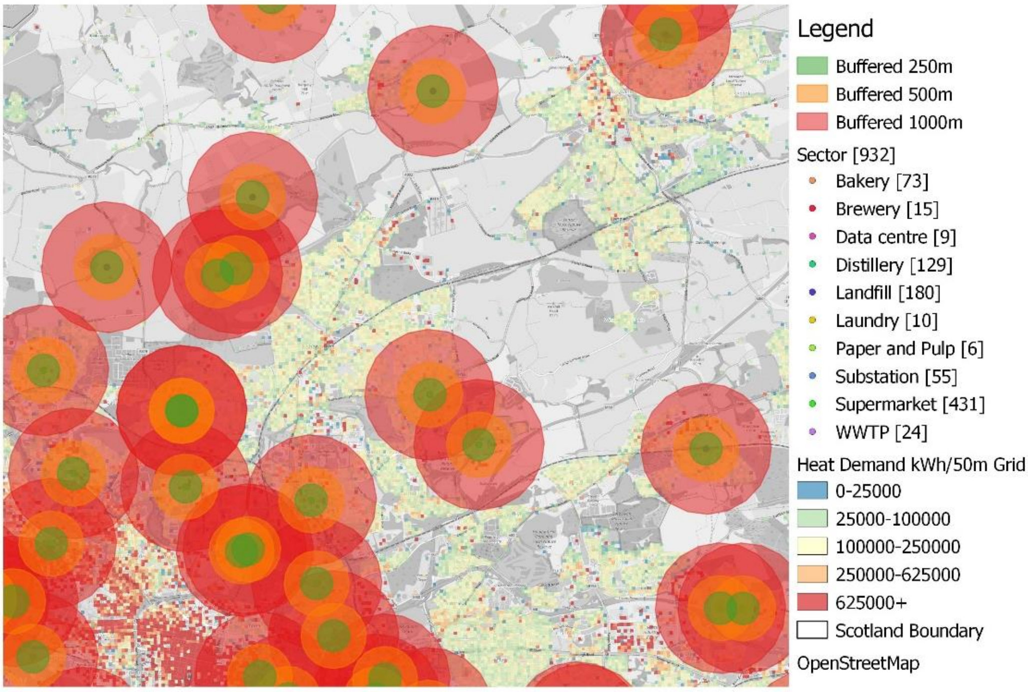

Figure 16: Example GIS view of showing heat demand and waste heat potential of different sites

The QGIS ‘Zonal Statistics’ function allows calculation of several values of pixels in a raster layer (i.e. heat map) with the help of a polygonal vector layer (i.e. buffers). For each site and for each buffer the count (the number of 50x50m grid squares presenting a heat demand (of any size)), sum (the total sum value of heat demand) and mean (the average value of heat demand) - a useful metric for comparing average heat density) was calculated. These data were presented for each site in the GIS map, as shown in Figure 18 below. Similar data for each site have been extracted to enable further analysis.

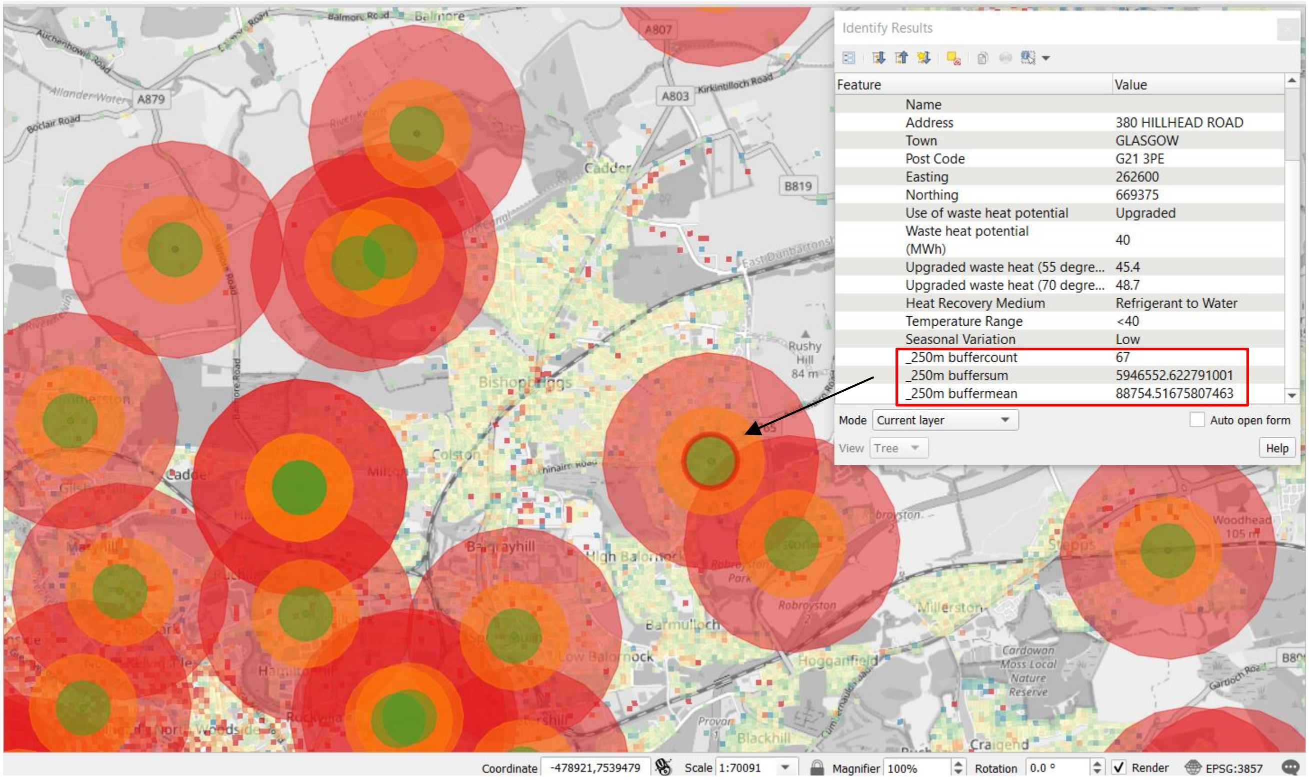

Figure 17: Example GIS view showing analysis of waste heat potential and heat demands within the buffers zone of an example site in Glasgow

This analysis identified the total heat demand within the (250m, 500m and 1km) buffer zones of all waste heat sites. Thereafter, we filtered out datapoints where total heat demand was less than 250 MWh in order to present the number of waste heat sites that could potentially meet nearby heat demand of this level.

A threshold of 250MWh was used as this represented the median figure of heat demand for existing DH schemes as calculated from the Scottish Government's 'Heat Networks Data 2020' database. The results of this analysis are presented below. When reading the results, it should be noted that only a simplified analysis has been undertaken (within the resources available for this research) and that more detailed analysis may be beneficial.

Table 4: Proximity analysis showing the number of sites that are within the buffer zone presenting greater than 250 MWh heat demand

	250m buffer zone		500m buffer zone		1km buffer zone	
	Total number of sites have heat demand >250MWh within the buffer zone	Total waste heat potential of the identified sites (MWh)	Total number of sites have heat demand >250MWh within the buffer zone	Total waste heat potential of the identified sites (MWh)	Total number of sites have heat demand >250MWh within the buffer zone	Total waste heat potential of the identified sites (MWh)
Data centres	9 (100%)	4,546	9 (100%)	4,546	9 (100%)	4,546
Distilleries	93 (72%)	265,800	114 (88%)	310,704	124 (96%)	315,992
Breweries	14 (93%)	977	14 (93%)	977	14 (93%)	977
Supermarkets	428 (99%)	69,485	429 (99%)	69,582	431 100%)	69,890
Laundry	10 (100%)	13,341	10 (100%)	13,341	10 (100%)	13,341
Paper & Pulp	6 (100%)	143,404	6 (100%)	143,404	6 (100%)	143,404
Substations	26 (47%)	18,650	36 (65%)	21,845	49 (89%)	30,421
WWTP	18 (75%)	289,051	23 (96%)	315,725	23 (96%)	315,725

Bakery	72 (99%)	185,370	72 (99%)	185,370	73 (100%)	187,040
Landfill	38 (21%)	3,488	85 (47%)	7,803	156 (87%)	14,321
Total	**714 (77%)**	**994,112**	**798 (86%)**	**1,073,297**	**881 (95%)**	**1,095,657**

As shown in Table 5 above, the results indicate that:

- A total of 714 waste heat sites (77% of all the sites assessed) have a heat demand greater than 250 MWh within 250m radius to each site. Landfills, substations and distilleries are the main sectors that have lower percentages of sites located within 250m of significant heat demand.
- A total of 798 waste heat sites (86% of all the sites assessed) have a heat demand of greater than 250 MWh within 500m radius, whereas 881 sites (95%) have a heat demand of more than 250 MWh within 1km radius. 1 distillery, 6 substations, 1 WWTP and 14 landfills are greater than 1km from 250 MWh of heat demand.

4.3.2 Proximity to existing district heating schemes

An additional assessment was undertaken to assess the proximity of waste heat sources to existing DH schemes[6] operating in Scotland. This analysis enabled us to determine what proportion of each of the heat sources is in close proximity to existing DH schemes in Scotland. It should be noted that DH schemes considered in this study include systems that fall within the Heat Network (Metering and Billing) Regulations 2014 and the Heat Network (Metering and Billing) (Amendment) Regulations 2015 (i.e. they range from relatively small-scale communal heating scheme to larger scale community heating schemes)

Table 6 presents the number of sites that have DH schemes within 250m, 500m and 1km distance.

Table 5: Proximity of waste heat sources to existing DH schemes

	250m buffer zone		500m buffer zone		1km buffer zone	
	Number of sites that have a DH scheme within the buffer zone	Waste heat potential of the identified sites (MWh)	Number of sites that have a DH scheme within the buffer zone	Waste heat potential of the identified sites (MWh)	Number of sites that have a DH scheme within the buffer zone	Waste heat potential of the identified sites (MWh)
Data centres	2 (22%)	1,056	4 (44%)	1,545	6 (67%)	2,196
Distilleries	3 (2%)	1,476	8 (6%)	48,256	22 (17%)	64,908
Breweries	4 (27%)	141	6 (40%)	230	10 (67%)	340
Supermarkets	70 (16%)	8,900	182 (42%)	28,215	299 (69%)	49,802
Laundry	0 (0%)	0	1 (10%)	1,779	4 (40%)	4,446
Paper and Pulp	0 (0%)	0	0 (0%)	0	1 (17%)	12,932
Substations	1 (2%)	802	7 (13%)	4,746	11 (20%)	8,592
WWTP	0 (0%)	0	1 (4%)	1,388	10 (42%)	108,797
Bakery	12 (16%)	25,050	25 (34%)	60,120	46 (63%)	120.240
Landfill	0 (0%)	0	3 (2%)	275	14 (8%)	1.377
Total	**92 (10%)**	**37,425**	**237 (25%)**	**146,554**	**423 (45%)**	**252,135**

The results suggest that:

[6] Operational DH schemes as identified within the Scottish Government's 'Heat Networks Data 2020' database -

- A total of 92 waste heat sites are within 250m distance of existing DH schemes. This is equivalent to 10% all waste heat sites identified in this study. The total waste heat potential of the identified sites is 37,245 MWh.
- Landfills, WWTPs, paper and pulp, and laundries do not have any existing DH schemes located within a 250m distance to each site whereas supermarkets, breweries, data centres and bakeries have relatively greater number of DH schemes located within a 250m radius.
- A total number of 237 sites (equivalent to 25% of all the waste heat sites identified in this study) are located within a 500m distance to an existing DH scheme. The total waste heat potential of the identified sites is 146,554 MWh.

A total number of 423 sites (equivalent to 45% of the all the waste heat sites identified) have an existing DH scheme located within 1km distance. Large facilities such as WWTPs, paper and pulp, and distilleries presented a relatively small number of sites within 1km of existing DH schemes. However, their waste heat potential is still very significant when compared to other waste heat sources. Landfill sites present the lowest percentage due to their locations typically being remote from densely populated areas.

2.4 Analysis of results per sector

4.4.1 Manufacture of beverages – breweries

- We identified a total number of 57 breweries (excluding micro-breweries). The production capacity of 42 breweries were estimated to be less than 3,000 hectolitres/year. Due to their very limited waste heat potential, we only mapped the results of 15 breweries with greater production capacity and thermal energy consumption (Figure 19).
- The total estimated waste heat potential is 992 MWh/year.
- The proximity analysis results show that 14 brewery sites (with a total waste heat potential of 977 MWh) have a heat demand greater than 250 MWh within a 250m buffer zone to each site.
- Four breweries (with a total waste heat potential of 141 MWh) are located within a 250m distance of existing DH schemes. A total number of 10 breweries (with a total waste heat potential of 340 MWh) are located within a 1km distance to existing DH schemes.
- We estimated the total amount of heat that could be recovered from the brewing process. The waste heat potential of brewery refrigeration systems was not investigated in this study.

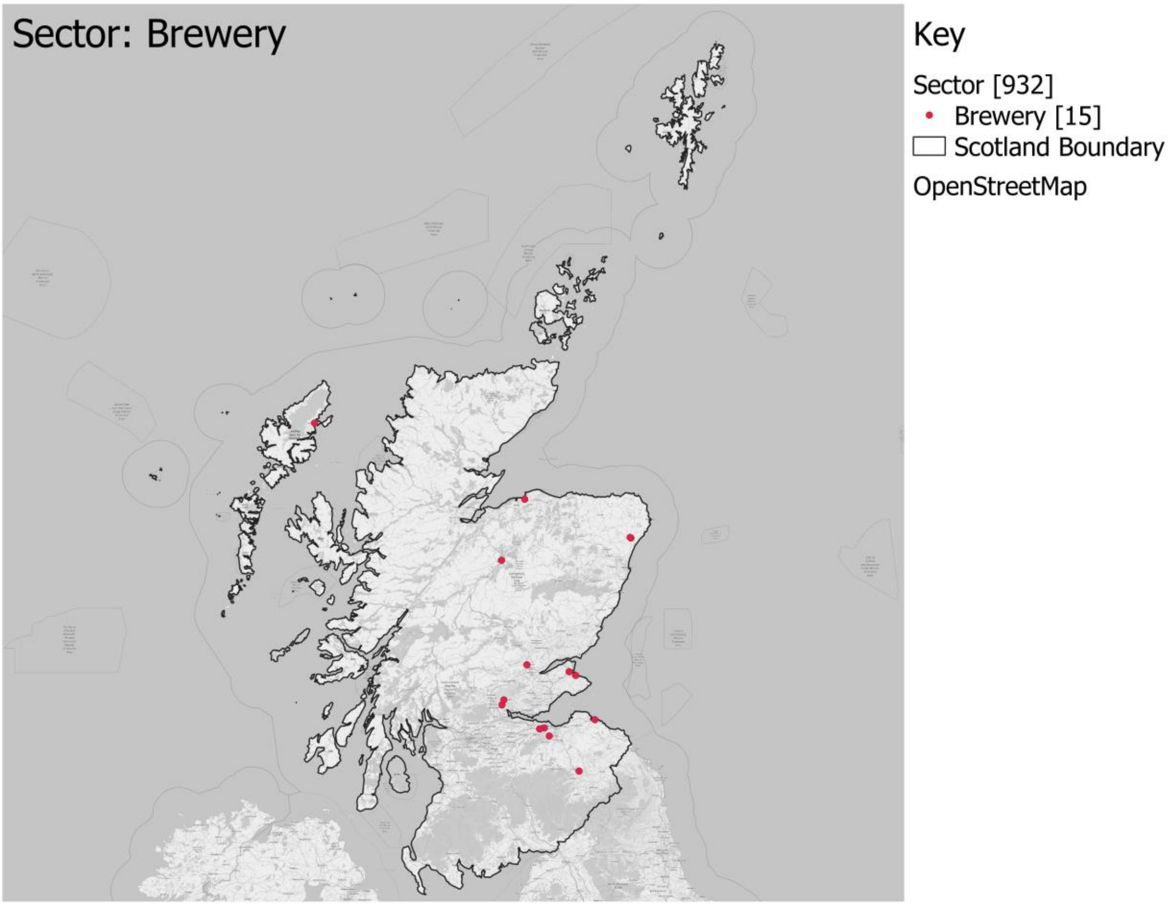

Figure 18: Brewery - potential sites for waste heat (number of sites in square brackets)

4.4.2 Manufacture of beverages – distilleries

- We identified a total number of 129 distilleries (7 grain, 122 malt distilleries). According to SEPA (2018), 40 new distilleries were at the planning stage in 2017. These were not included in this study.
- The total estimated waste heat potential of the sector is 320,104 MWh/year.
- Based on the proximity analysis, 93 distilleries (with a total waste heat potential of 265,800 MWh) have a heat demand greater than 250 MWh within a 250m buffer zone, showing a relatively good potential for waste heat reuse opportunities.
- It was found that three distilleries (presenting a waste heat potential of 1,476 MWh) are located within a 250m distance of existing DH schemes. A total number of 22 distilleries (presenting a waste heat potential of 64,908 MWh) are located within a 1km distance of existing DH schemes.
- Due to significantly large production capacity (>10,000,000 LPA) of 15 distilleries, the overall waste heat potential of the sector is very high. However, it must be noted that large distilleries might already have energy efficient processes (including heat recovery) in place. Due to lack of information available on site-specific thermal energy consumption, we applied a standard Specific Energy Consumption rate to all the distilleries. In reality, specific thermal energy consumption rate might vary depending on production capacity.

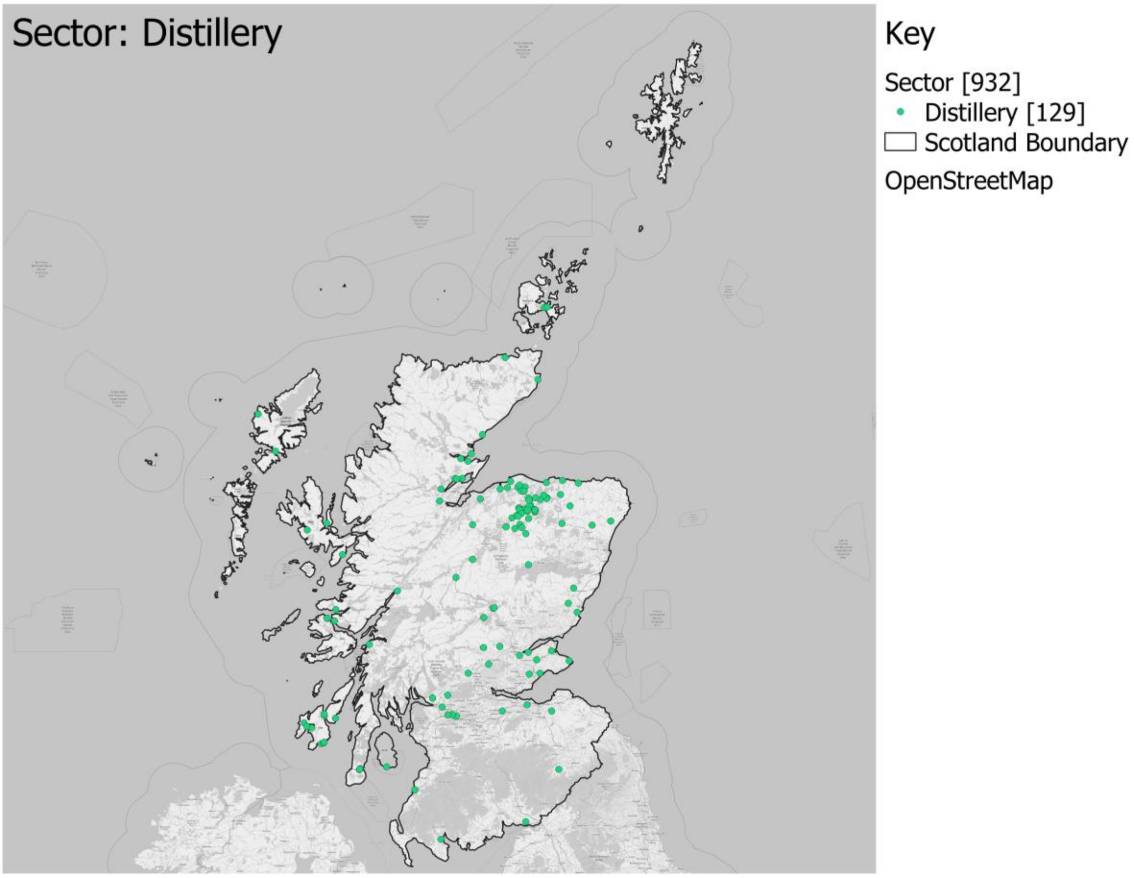

Figure 19: Distillery - potential sites for waste heat (number of sites in square brackets)

4.4.3 Manufacture of paper and paper products

- In this study, we identified a total of six sites with an estimated total thermal energy consumption of 1,600 GWh per year.
- The total waste heat potential of this sector is very significant (143,405 MWh/year) in comparison to other sectors due to its relatively high thermal energy consumption.
- Depending on site specific characteristics, high-grade heat could also be recovered from paper and pulp mills.
- The total estimated waste heat potential of this sector is 143,901 MWh/year.
- The proximity analysis show that all the paper and pulp sites mapped in this study have a heat demand greater than 250 MWh in their local areas (considering a 250m buffer zone).
- None of the paper and pulp sites have an existing DH scheme located within a 500m distance. One paper and pulp site (with a waste heat potential of 12,932 MWh) is located approximately 1km from an existing DH scheme.

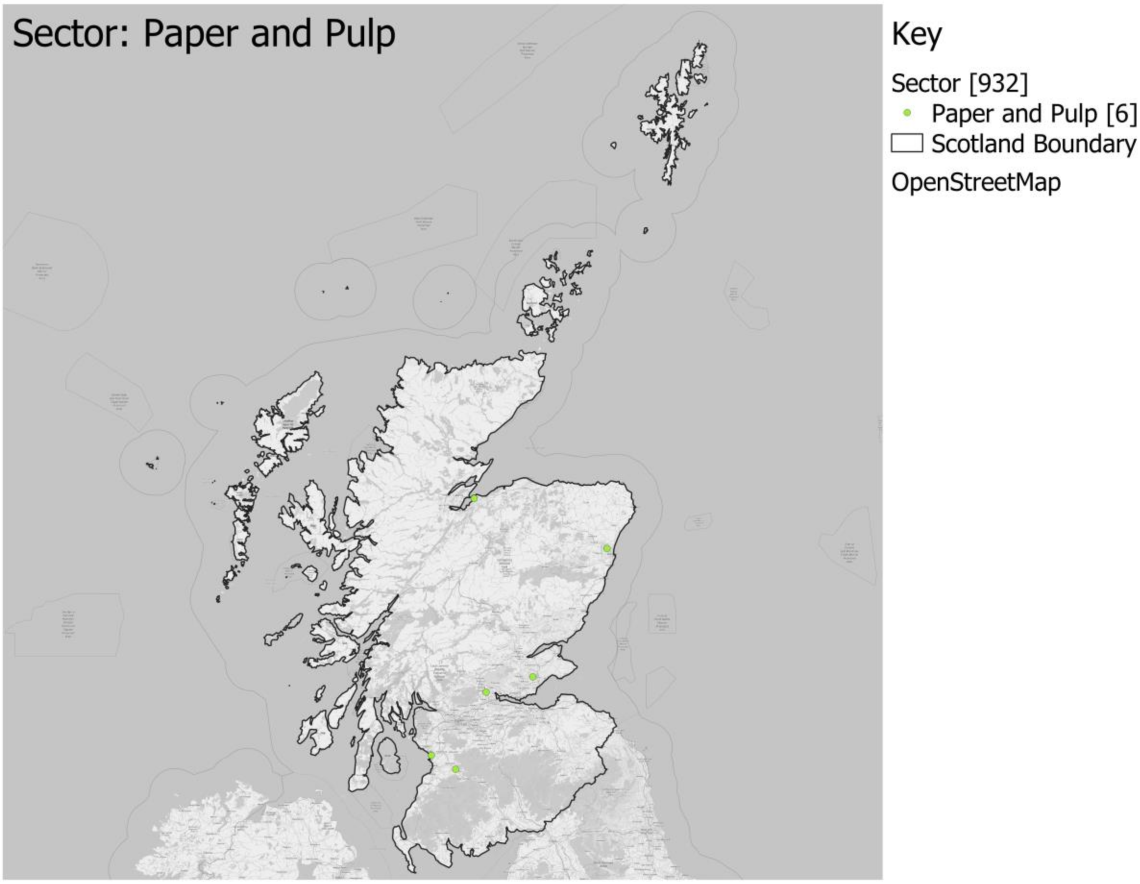

Figure 20: Paper and pulp – potential sites for waste heat (number of sites in square brackets)

4.4.4 Data centres

- Based on publicly available data, we identified nine active data centres in Scotland, with an estimated direct waste heat potential of 4,548 MWh per year.
- The upgraded waste heat potential at 55ºC and 70ºC are, respectively, 5,101 MWh/year (requiring an electricity input of 554 MWh/year) and 5,474 MWh/year (requiring an electricity input of 928 MWh/year).
- The proximity analysis show that all the data centres sites mapped in this study have a heat demand greater than 250 MWh in their local areas (250m buffer zones).
- Two data centres (with a total waste heat potential of 1,056 MWh) are located within a 250m distance of existing DH schemes. A total number of six data centres (with a total waste heat potential of 2,196 MWH) are located within a 1km distance of existing DH schemes.
- The peak of available waste heat coming from cooling systems is likely to occur in the summer, when heat demand is low. This, in turn, might limit the opportunities for the effective use of waste heat for district heating purposes.
- There was very limited information about data centre energy benchmarks and cooling loads in Scotland. Further research is required to assess cooling loads using monitoring datasets.

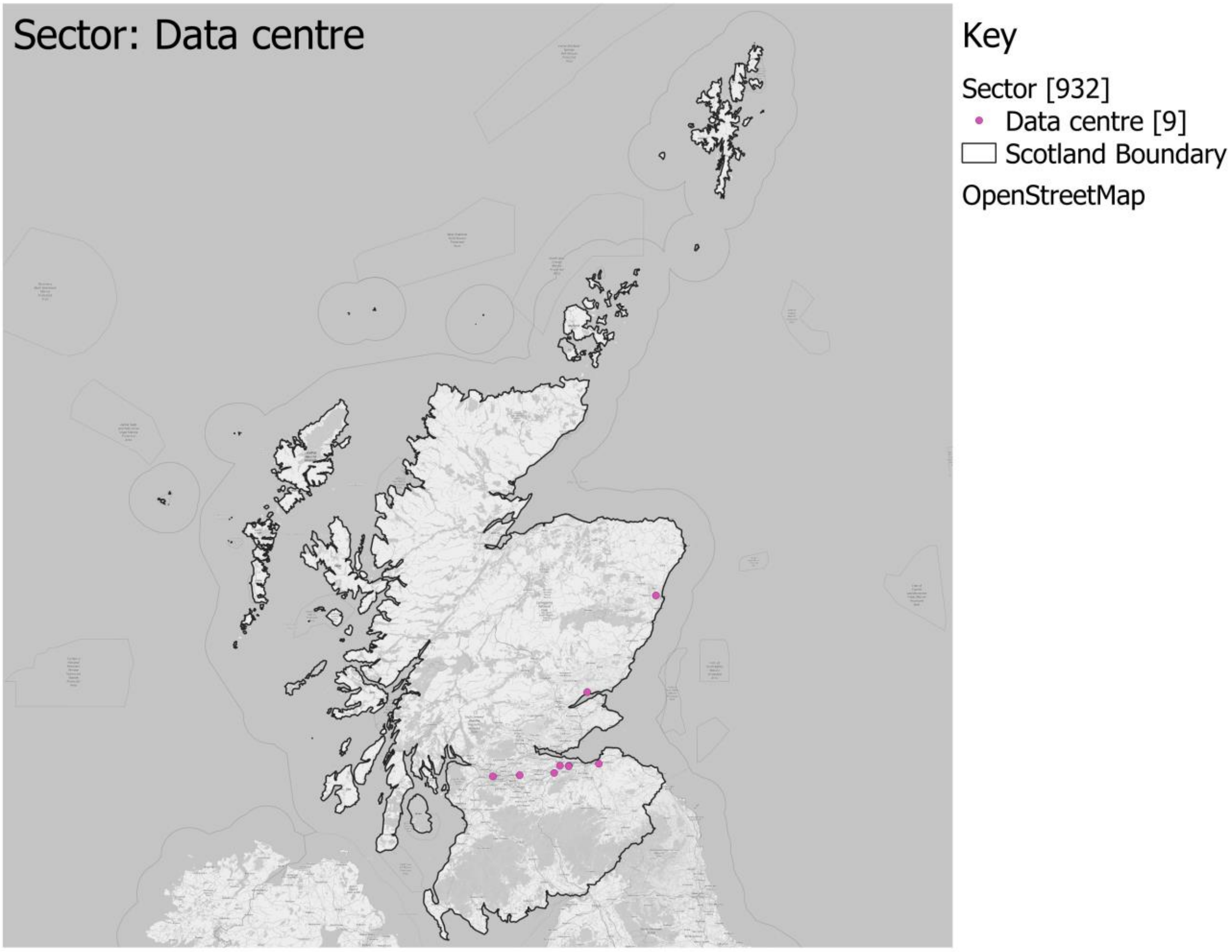

Figure 21: Data centres - potential sites for waste heat (number of sites in square brackets)

4.4.5 Supermarkets

- In this study, we identified 431 large supermarkets (with a gross floor area greater than 750 m^2. The total direct waste heat potential was estimated to be approximately 69,889 MWh per year.
- Low-grade heat recovered from condensers could be upgraded to a higher temperature by using heat pumps and then, used for other applications. The upgraded waste heat potential at 55ºC and 70ºC are, respectively, 78,412 MWh/year (requiring an electricity input of 8,523 MWh/year) and 84,152 MWh/year (requiring an electricity input of 14,263 MWh/year).
- The proximity analysis suggests that the local heat demand (considering a 250m buffer zone) of 428 supermarkets mapped in this study is greater than 250 MWh. This in turn indicates a good potential for waste heat reuse opportunities.
- 70 supermarkets are located within a 250m distance of existing DH schemes. A total number of 299 supermarkets (with a total waste heat potential of 49,802 MWh/year) are located within a 1km distance from existing DH schemes.
- At large supermarkets with central refrigeration systems, medium-grade (between 60ºC and 90ºC) can be available from 'de-superheating[7]' process. This could be also

[7] De-superheating process: Cooling down of the superheated refrigerant.

potentially recovered and used for district heating applications without using a heat pump system (Carbon Trust, 2020).

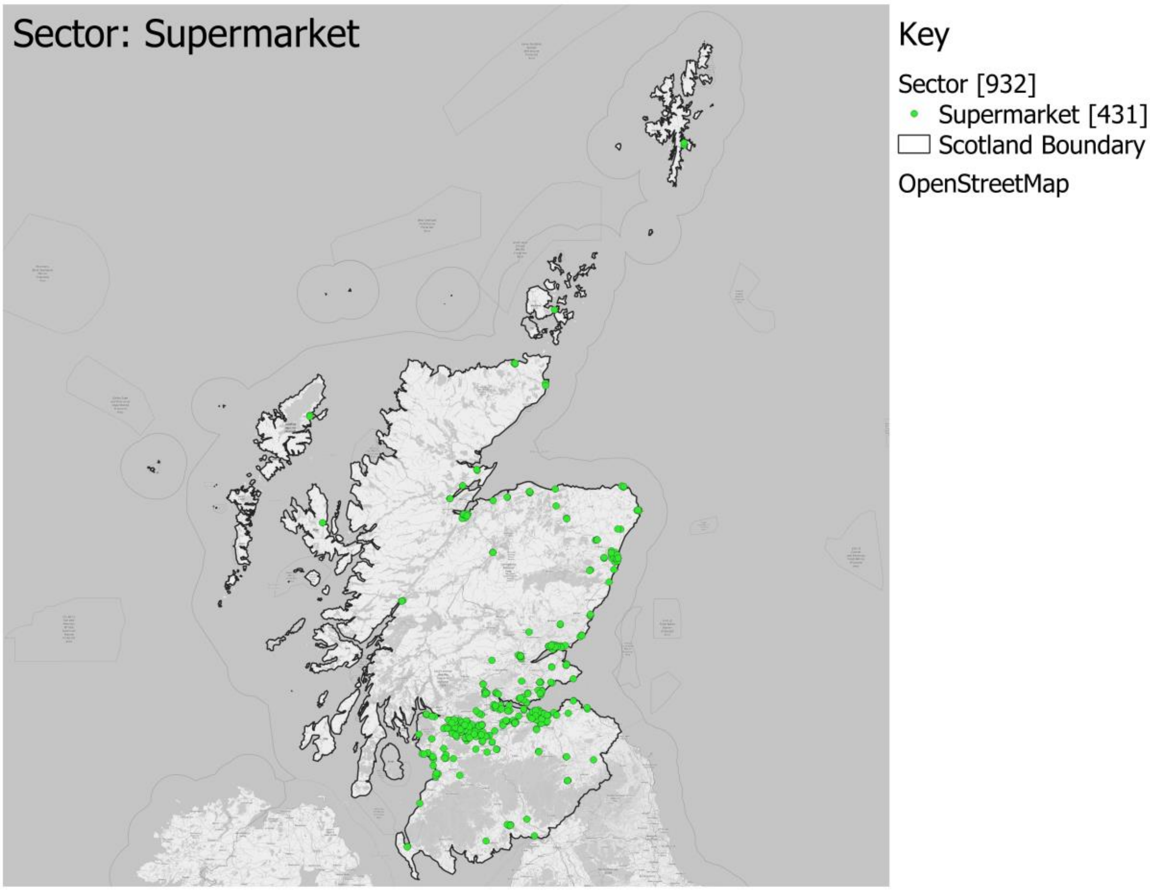

Figure 22: Supermarkets - potential sites for waste heat (number of sites in square brackets)

4.4.6 Industrial laundry facilities

- We identified a total of 10 industrial laundry sites, with an estimated waste heat potential of 13,341 MWh/year.
- The proximity analysis suggests that the local heat demand (considering a 250m buffer zone) of all the laundry sites is greater than 250 MWh.
- None of the laundry sites have an existing DH scheme located within a 250m radius. A total number of 4 sites (with a total waste heat potential of 4,446 MWh) are located within a 1km distance of existing DH schemes.
- Washing, drying and finishing operations (such as ironing) could provide significant potential for exhaust heat recovery applications.
- Further research is required to gather up-to-date information on sector specific thermal energy consumption and heat recovery opportunities.

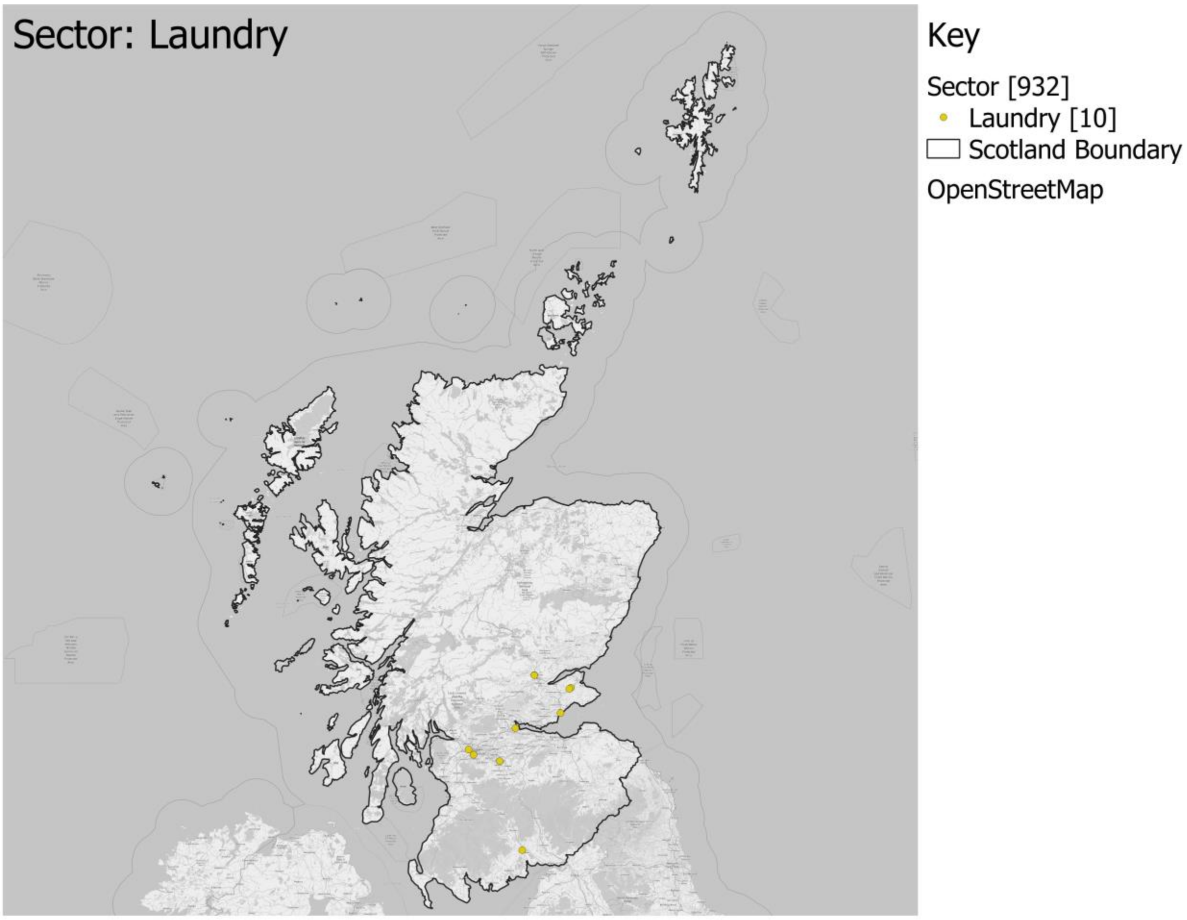

Figure 23: Laundry - potential sites for waste heat (number of sites in square brackets)

4.4.7 Bakery

- We identified a total of 73 industrial and large-scale bakeries with an estimated waste heat potential of 187,040 MWh/year.
- The proximity analysis suggests that the local heat demand (considering a 250m buffer zone) of 72 bakeries is greater than 250 MWh. This indicates a good potential for waste heat reuse opportunities in nearby sites.
- 12 bakeries (with a total waste heat potential of 25,050 MWh) are located within a 250m distance of existing DH schemes. A total number of 46 bakeries are located within a 1km distance of existing DH schemes, presenting a waste heat potential of 120,240 MWh. This in turn indicates a good potential for the use of waste heat in nearby DH schemes.
- Further research is required to gather up-to-date information on sector specific thermal energy consumption and heat recovery opportunities.

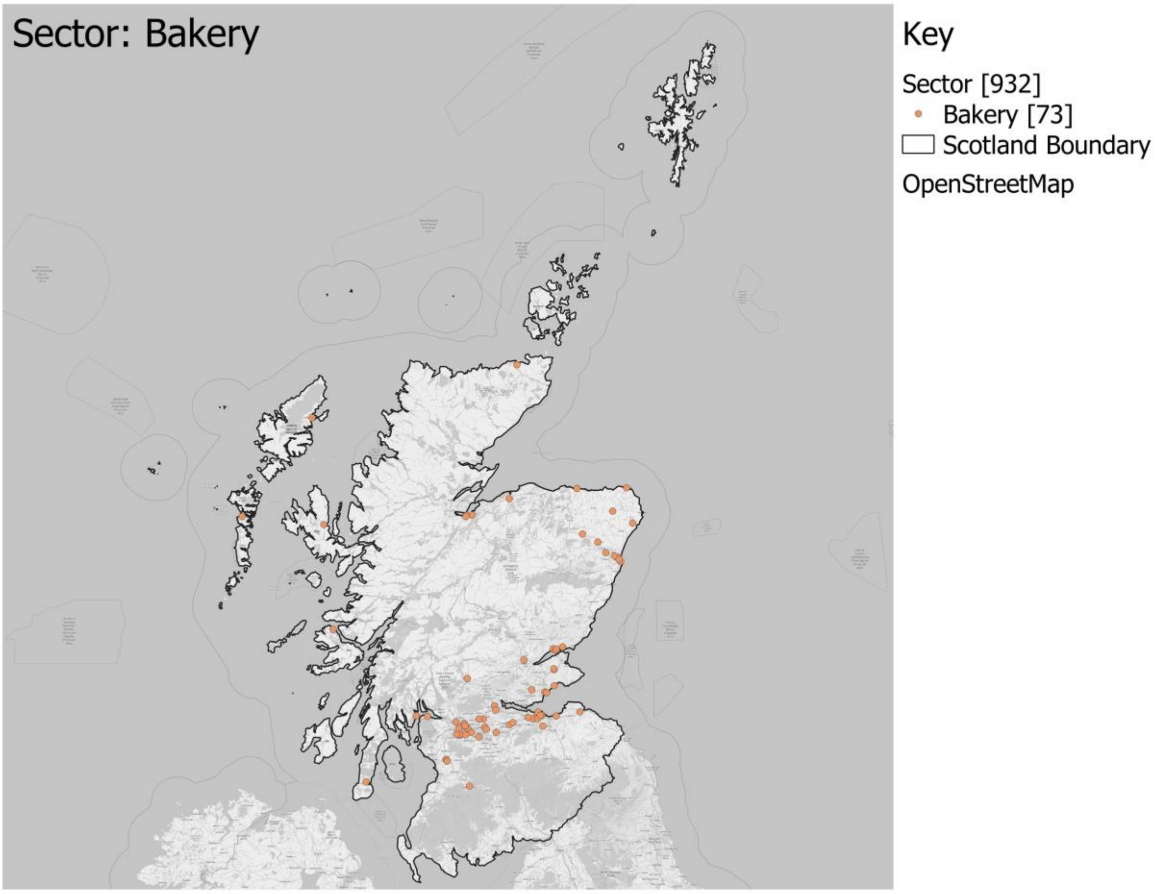

Figure 24: Bakeries - potential sites for waste heat (number of sites in square brackets)

4.4.8 Waste-water treatment plants

- At waste-water treatment plants, waste-water heat recovery can be applied after the treatment process, as the reduced effluent temperature can also create a positive impact to environment (Jouhara, et al., 2018)
- In this study, we identified a total of 34 waste-water treatment plants based on the information provided by Scottish Water Horizons. Flow rate data for only 24 waste-water treatment plants were available. As a result, we only estimated the waste heat potential of 24 WWTPs.
- The effluent temperature of the WWTPs in our dataset varies between 1^{o}C and 21^{o}C throughout the year. The average effluent flow rate was estimated to be 55,200m^3/day per site. The total estimated waste heat potential is 318,907 MWh/year.
- The upgraded waste heat potential at 55^{o}C and 70^{o}C are, respectively, 402,827 MWh/year (requiring an electricity input of 83,922 MWh/year) and 425,206 MWh/year (requiring an electricity input of 106,302 MWh/year).
- The proximity analysis suggests that the local heat demand (considering a 250m buffer zone) of 18 WWTPs is greater than 250 MWh.
- None of the WWTPs are located within a 250m distance of any existing DH schemes. A total number of 10 WWTPs (with a total waste heat potential of 108,797 MWh) are located within a 1km distance of existing DH schemes.

- Due to significantly high capacity and flow rate of WWTPs located in urban areas (such as Edinburgh and Glasgow), the overall waste heat potential of this sector is very high. More research is required to understand the potential impact of high flow rate on heat pump efficiency and operation.

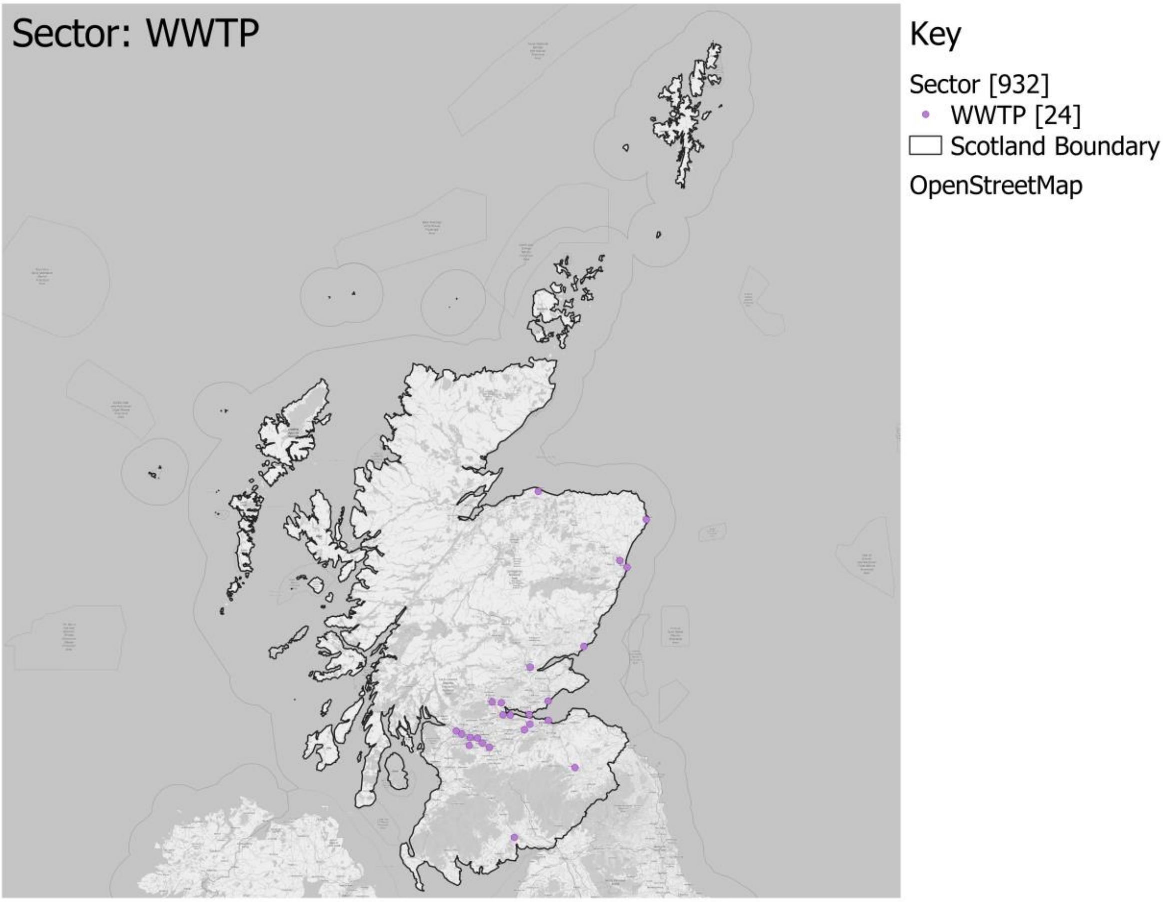

Figure 25: WWTPs - potential sites for waste heat (number of sites in square brackets)

4.4.9 Electricity substations

- We identified a total of 55 substations related to the SSE Networks area. It should be noted that no data was available for the south of Scotland from SP Energy Networks.
- The amount of waste heat that can be captured depends on the transformer cooling method. The waste heat potential of different transformer cooling methods can be summarised as (Imperial College London; Sohn Associates, 2014):

  Oil Natural Air Natural (ONAN) – Low heat recovery potential

  Oil Natural Air Forced (ONAF) – Medium heat recovery potential

  Oil Forced Air Forced (OFAF) – Medium heat recovery potential

  Oil Forced Water Forced (OFWF) – High heat recovery potential

  Oil Directed Air Forced (ODAF) – Medium heat recovery potential

  Oil Directed Water Forced (ODWF) – High heat recovery potential
- Due to lack of publicly available information on transformer cooling types, we were not able to identify the transformers with OFWF and ODWF cooling.

- We focused on the waste heat potential of large-scale transformers with a minimum capacity of 132/11 kV, as they are likely to provide an opportunity for waste heat recovery.
- Overall, the total direct waste heat potential of substations was estimated to be 31,350 MWh.
- The upgraded waste heat potential at 55ºC and 70ºC are, respectively, 33,215 MWh/year (requiring an electricity input of 1,909 MWh/year) and 35,843 MWh/year (requiring an electricity input of 4,537 MWh/year).
- The proximity analysis suggests that 53% of the substations mapped in this study do not have a very significant heat demand in their local areas (considering a 250m buffer zone and a 250 MWh heat demand threshold), indicating a low potential for the use of waste heat at a nearby site.
- Only one substation is located within a 250m distance of an existing DH scheme. A total number of 11 substations (with a total waste heat potential of 8,592 MWh) are located within a 1km distance of existing DH schemes.

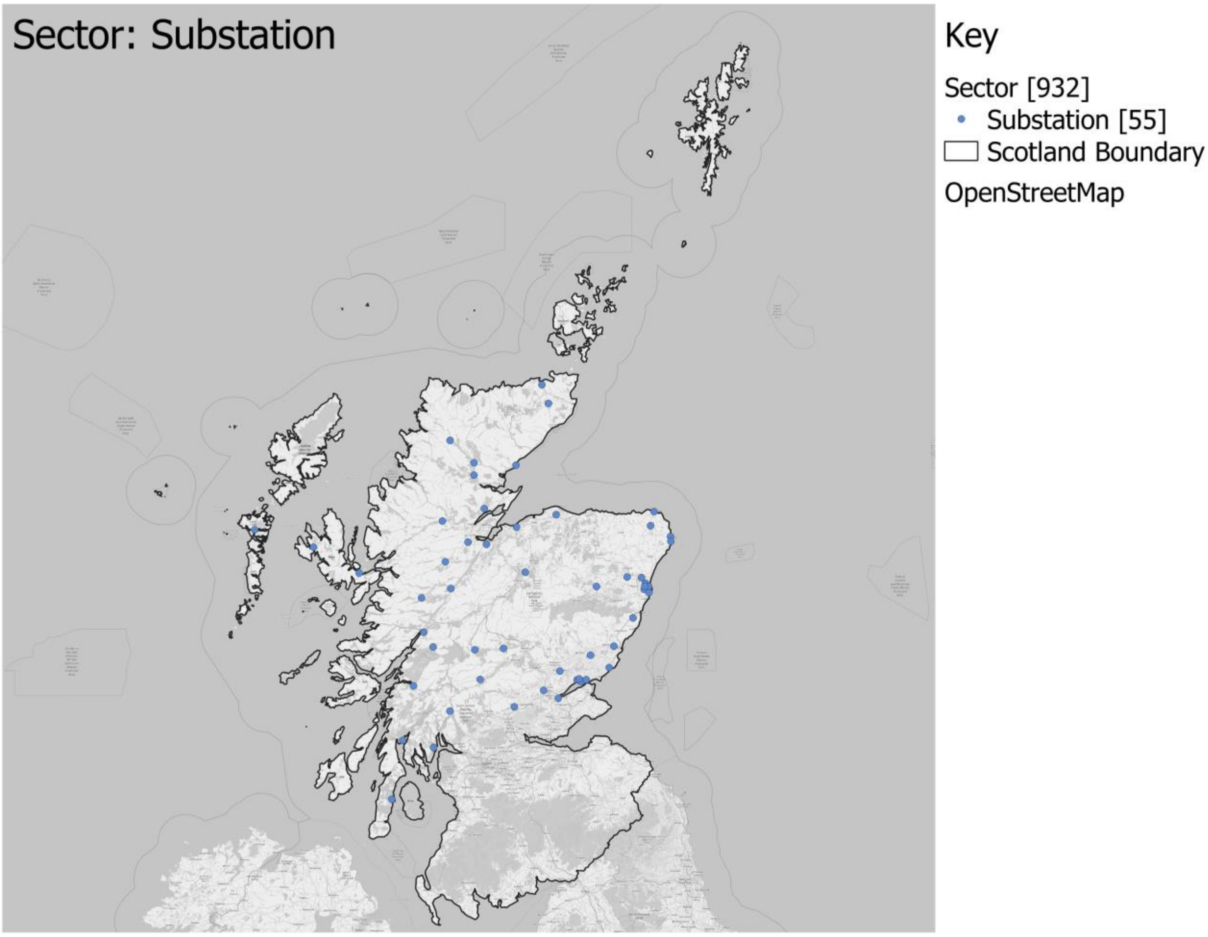

Figure 26: Electricity substations - potential sites for waste heat (number of sites in square brackets)

4.4.10 Landfill sites

- We identified a total of 180 inactive landfill sites in Scotland.
- The estimated direct waste heat potential of landfill ground source system is 13,680 MWh/year.

- The upgraded waste heat potential at 55ºC and 70ºC are, respectively, 15,530 MWh/year (requiring an electricity input of 2,850 MWh/year) and 17,589 MWh/year (requiring an electricity input of 3,909 MWh/year).
- The proximity analysis suggests that 79% of the inactive landfills mapped in this study do not have a very significant heat demand in their local areas (considering a 250m buffer zone and a 250 MWh heat demand threshold).
- There are no existing DH schemes within a 250m distance of any inactive landfills. A total number of 14 landfills (with a total waste heat potential of 1,377 MWh) are located within a 1km distance of existing DH schemes, indicating low potential for the use of waste heat in existing DH schemes.
- Previous case studies show the high level of efficiency and cost effectiveness of landfill based shallow geothermal systems, with simple payback periods in the range of four to seven years (Grillo, 2014). Further research is needed to assess the technical constraints of such applications, using monitoring data (ground temperature) of inactive landfills in Scotland.

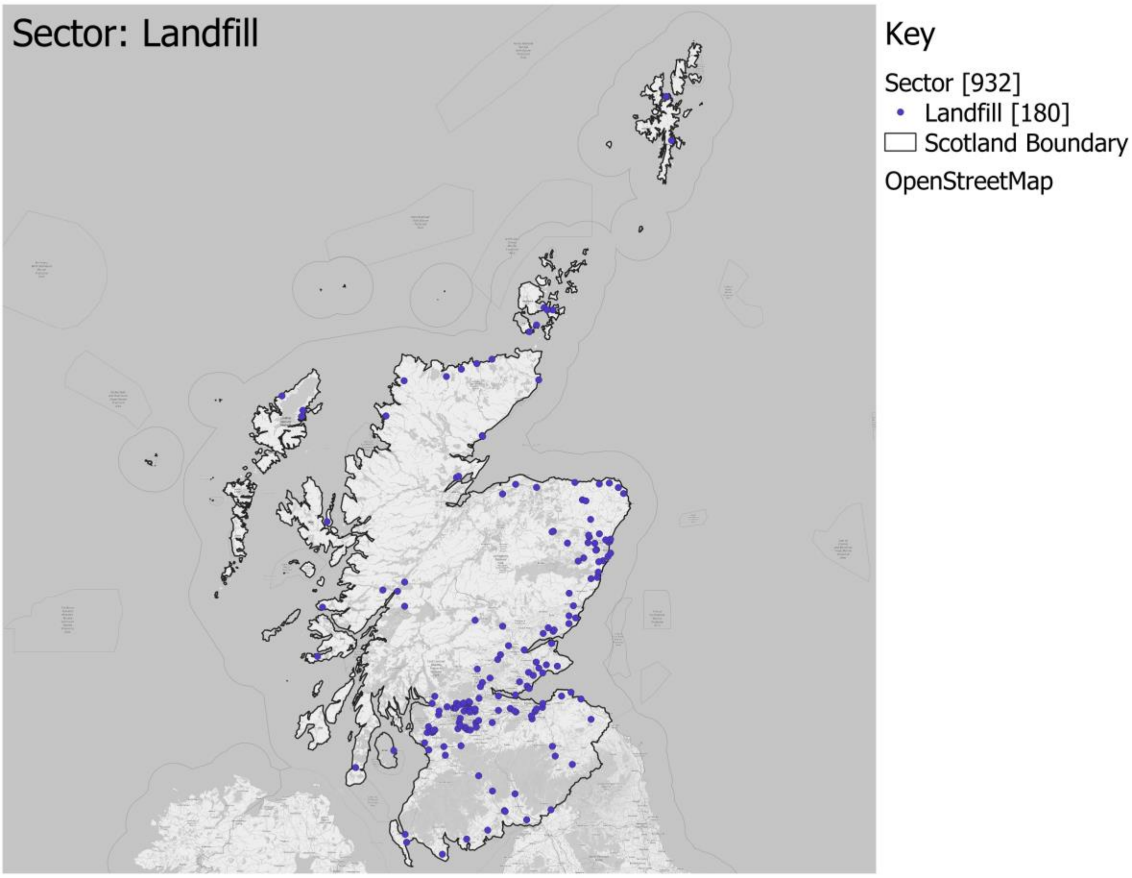

Figure 27: Landfill - potential sites for waste heat (number of sites in square brackets)

2.5 Seasonal variation

When evaluating the suitability of waste heat sources, and their potential to contribute to meeting heating demand, it is important to consider the extent to which the various heat sources availability ‘matches’ the heating demand i.e. space heating demand in Scotland is significantly higher in winter than in summer. It is therefore likely to be more economically advantageous to help meet this demand via a heat sources that provides more energy in winter than in summer. Of course, energy storage systems (e.g. ranging from short-term storage to inter-seasonal storage) can help; however, they can add significant cost to development. The seasonal variation of waste heat sources varies depending on their physical properties, operational requirements, load profiles and external conditions. In this study, we undertook a high-level assessment of the likely seasonal variation of waste heat sources using a relative scale (Low, Medium, High potential for seasonal variability) based on our research findings and discussions with key stakeholders. It should also be noted that other significant variations between the supply and demand profiles (e.g. hourly, daily, etc.) are equally important considerations when evaluating the technical-economic viability of recovering and using waste heat sources, particularly low-grade sources. Detailed analysis of the potential impacts of seasonal variation and supply/demand matching was, however, out with the scope of this study.

Table 6: Seasonal variation of waste heat temperature and usable waste heat

	Source of Waste Heat	Potential for Seasonal Variation – Usable waste heat	Seasonal Temperature Variation	Notes
Industrial Processes	Bakeries	Low	Low	Industrial processes are likely to have low level seasonal variation in waste heat temperature and availability. Operation hours and load patterns are however likely to vary at each site.
	Breweries	Low	Low	
	Distilleries	Low	Low	
	Paper and pulp	Low	Low	
	Industrial laundry	Low	Low	
Commercial	Data centres	Medium – Likely to reduce in winter	Medium – Likely to reduce in winter	Data centres’ cooling load are likely to vary throughout the year i.e. a higher waste heat potential will be present in summer, as opposed to winter (when the lower external temperature helps reduce the cooling requirement).
	Supermarkets	Low	Low	Supermarkets’ refrigeration loads are expected to be more consistent in comparison to data centres. However, due to lower external temperature in winter, the refrigerant loads might slightly decrease during the heating season.

Waste water	Waste-water treatment plants	Medium – Likely to reduce in Winter	High- Likely to reduce in Winter	Effluent water temperature at waste-water treatment plants tend to vary significantly throughout the year. This is mainly due to lower temperature surface run-off and rainwater. Other external conditions also impact the waste-water temperature. The amount of waste heat that can be captured in winter is likely to be less than the heat that can be captured in summer. The waste-water flow rate tends to remain relatively stable throughout the year.
Electricity	Electricity sub-stations	Medium – Likely to fluctuate throughout the year	Medium	The cooling load of transformers is expected to vary throughout the year due to changes in transformer loads and external temperature. More research required to assess potential changes in transformer loads and the likely impacts on waste heat potential.
Landfill	Landfill heat	Low	Low	Landfill temperature is likely to remain relatively constant throughout the year.

3 Conclusions and recommendations

3.1 Conclusions

This study examines a variety of potential waste heat sources in Scotland, quantifies their potential and maps and analyses them in GIS. It assesses the waste heat potential of 10 different sectors using a variety of data sources and calculation steps (including excluding significantly small sites, applying assumptions on site activities and energy consumption, etc.). We assess the proximity of individual waste heat sources to existing heat demand points. We also assess the level of heat demand in relatively close proximity to each waste heat site and analyse the supply and demand levels. Results are represented in a GIS map and a supporting master data spreadsheet.

The following conclusions are drawn:

- The study identifies a total of 932 waste heat sites in Scotland. This comprises 233 medium-grade waste heat sites (50-150ºC) (presenting an estimated direct use energy potential of 665 GWh) and 699 low-grade waste heat sites (<50ºC) (presenting an estimated energy potential of 438 GWh (direct, <50ºC), 536 GWh (upgraded via heat pump to 55ºC, requiring an electricity input of 98 GWh) and 568 GWh (upgraded via a heat pump to 70ºC, requiring an electricity input of 130 GWh).
- The largest estimated waste heat potential is in the distillery and waste-water treatment sectors. With the implementation of suitable heat recovery methods (i.e. water-to-water

heat pumps), significant amounts of heat can be recovered and re-used. Bakeries and paper and pulp are the other sectors with large waste heat potential.

- Data centres, supermarkets and breweries have relatively lower waste heat potential in comparison to other sectors. The amount of waste heat available from cooling systems (data centres and substations) will be higher in the summer i.e. when heat demand will be lower. This may therefore limit the opportunities for the effective use of waste heat for district heating purposes.
- A proximity analysis identifies that 714 waste heat sites (77% of all the sites assessed, presenting a total waste heat potential of 994,112 MWh) have a heat demand greater than 250 MWh within 250m radius of their site. 798 waste heat sites (86% of all the sites assessed) have a heat demand of greater than 250 MWh within 500m radius, and 881 sites (95%) have a heat demand of more than 250 MWh within 1km radius. Data centres, breweries, supermarkets, laundries, bakeries and paper and pulp sites have relatively high demand in their local areas. As a result, these may provide potential for district heating opportunities. As this was a simplified proximity analysis, it would be advantageous to conduct more detailed analysis of the opportunities for supply / demand matching.
- Additional analysis identifies that 237 sites (equivalent to 25% of all the waste heat sites identified in this study) have an existing DH scheme within 500m. Distilleries, laundries, WWTPs, landfills and paper and pulp sites have a relatively low number of sites located within 500m of DH schemes. On the other hand, supermarkets, data centres and bakeries have a relatively high number of sites located within 500m of DH schemes.

3.2 Recommendations

- The actual heat that can be recovered from a system depends on the selection and design of heat recovery methods and the quality of waste heat. It is therefore suggested that further work be undertaken to investigate the commercial and technological aspects of waste heat recovery from WWTPs, distilleries and paper and pulp mills, as these sectors have relatively higher theoretical waste heat potential and are in close proximity to heat demand.
- The potential for waste heat recovery from (i) electrical substations in the central / south of Scotland, (ii) sewer networks, and (iii) food manufacturing sites should be investigated further as it was not possible to obtain data on, or analyse, these sources within the project.
- There is a need to review and assess the heat recovery potential, and the technologies suitable for recovering, the waste heat of electricity substations. Although the theoretical waste heat potential is relatively significant, techno-commercial barriers need to be considered and assessed.
- The viable distance for the transport and use of waste heat will vary depending on several factors including its temperature and flowrate (i.e. energy quantity and quality), the temperature difference / gradient between the waste heat and the heat network, and the supply and demand profiles. Further research in this area and/or reviews of the technical and commercial aspects of recovering and re-using waste heat in district heating systems would be advantageous.
- As only a simplified proximity analysis was undertaken within the project, it would be advantageous to conduct more detailed analysis to explore the opportunities for supply / demand matching.

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5 Appendices

Appendix A: Outline of scoping activity

The following table shows the scoping activity. We reviewed the industry-based energy consumption data published by the UK Government Department for Business, Energy and Industrial Strategy (BEIS, 2020) and we shortlisted the most energy intensive industrial sectors.

As the (BEIS) sector-level energy consumption data was only available for the whole of the UK and not sub-divided for Scotland, we reviewed the Gross Value Added (GVA) statistics of the energy intensive industries shortlisted above and identified the sectors with greatest contribution to the Scottish economy (The Scottish Government, 2018). The shortlisted sectors were then subjectively rated (green, amber, red) based on their likely waste heat potential. The ratings drew upon the findings and conclusions from previous studies.

SIC	Heat Source	UK Energy Consumption (BEIS, 2020)	Potential site opportunities based on GVA statistics[8] (The Scottish Government, 2018)	Potential for heat reuse	Priority for investigation in this study
	Industrial Processes				
23	Manufacture of non-metallic mineral products	1,737 ktoe	Medium	High	Medium
24	Manufacture of basic metals	1,281 ktoe	Low	High	Low
10	Manufacture of food products	1,461 ktoe	Very High	High	High
20	Manufacture of chemicals and chemical products	861 ktoe	High	High	Medium
25	Manufacture of fabricated metal products	518 ktoe	High	Low	Low
22	Manufacture of rubber and plastic products	440 ktoe	Medium	High	Medium
11	Manufacture of beverages	350 ktoe	Very High	High	High
29	Manufacture of machinery and equipment	320 ktoe	Medium	Medium	Medium
17	Manufacture of paper and paper products	242 ktoe	Medium	High	High
29	Manufacture of motor vehicles, trailers and semi-trailers	242 ktoe	Medium	High	Medium
16	Manufacture of wood and of products of wood and cork.	104 ktoe	Medium	High	Medium
	Commercial				
63.11	Data processing, hosting and related activities; web portals (Data centres)	Unknown	Unknown	Medium	High
96.01	Washing and (dry-)cleaning of textile and fur products	Unknown	Low	High	High
47.11	Retail sale in non-specialised stores with food, beverages or tobacco (Supermarkets)	1007 ktoe	Unknown	Medium	High
86.10	Hospital activities	2205 ktoe	Unknown	High	Medium
N/A	**Waste-water treatment plants**	N/A	N/A	High	High
N/A	**Sewer network**	N/A	N/A	High	High
N/A	**Electricity sub-station**	N/A	N/A	Medium	Medium
N/A	**Underground cable ducts**	N/A	N/A	Low	Low
N/A	**Landfill heat**	N/A	N/A	High	High
N/A	**Minewater**	N/A	N/A	High	Low
N/A	**Power stations**	N/A	N/A	Medium	Low
N/A	**Underground train stations**	N/A	N/A	Low	Low

[8] A subjective assessment has been carried out after reviewing the GVA statistics of each sector.

Appendix B: Data sources

Source	Website
SEPA Pollution Inventory	https://www.sepa.org.uk/environment/environmental-data/spri/
Environment Map - Scottish Government	https://map.environment.gov.scot/sewebmap/
Heat Map - Scottish Government	http://heatmap.scotland.gov.uk/
Data Center Map	https://www.datacentermap.com/
Scottish Industry Directories	https://directories.scot/
Scottish Assessor Association	https://www.saa.gov.uk/
Scottish Water Asset Plans	https://www.scottishwater.co.uk/business-and-developers/connecting-to-our-network/pre-development-information/asset-plans
SSEN Electricity Substation Map	https://www.ssen.co.uk/ContractedDemandMap/?mapareaid=2
Whisky Invest Direct	https://www.whiskyinvestdirect.com/about-whisky/malt-whisky-distilleries-in-scotland
Scotland's Whisky Map	https://www.visitscotland.com/see-do/food-drink/whisky/distilleries/
SEPA – Scotland's Waste Site and Capacity Map	https://www.sepa.org.uk/data-visualisation/waste-sites-and-capacity-tool/

Appendix C: Approach

The following table shows the individual methodologies and assumptions applied.

Source of Waste Heat		Methodology
Bakeries	Approach	Heat Extraction: Flue gas The thermal energy consumption of each site was estimated based on the Rateable Value of each bakery. Apply 10% heat recovery ratio to estimate the potential waste heat available.
	Assumptions	Heat recovery fraction was assumed to be 10%. Oven thermal consumption was assumed to be 1.67 kWh/kg (Paton Bramwell, 2013). Location dataset based on data extracted from the SAA assessor role.
Breweries	Approach	Heat Extraction: Flue gas The thermal energy consumption of each site was estimated based on the average rated value per hectolitre of beer produced per year. Apply 10% heat recovery ratio to estimate the potential waste heat available. Breweries with a capacity less than 3,000 hectolitres/year were not included in the analysis due to their low potential for heat recovery.
	Assumptions	Brewery thermal energy consumption: 41 kWh/bbl (Brewers Association, 2020). Heat recovery fraction was assumed to be 10% (McKenna & Norman, 2010). Fuel to heat ratio of 0.8 (McKenna & Norman, 2010). Location dataset based on data extracted from the SAA assessor role. Brewery production capacity was estimated using various manufacturer sources and SAA data.
Distilleries	Approach	Heat Extraction: Flue gas The thermal energy consumption of each site was estimated using site-specific whisky production data. Apply 10% heat recovery ratio to estimate the potential heat energy available.
	Assumptions	Distillery specific energy consumption[9]: 6.66 kWh/LPA Natural gas consumption ratio: 0.76 (McKenna & Norman, 2010)

[9] https://publications.parliament.uk/pa/cm200708/cmselect/cmenvaud/354/354we04.htm

		Fuel to heat ratio: 0.8 (McKenna & Norman, 2010) Location dataset based on data extracted from the SAA assessor role. Distillery production capacity published by Whisky Invest[10].
Paper and Paper products	Approach	Heat Extraction: Flue gas The total energy consumption of each site was estimated using the CO2 emission data published by SEPA. Estimate the total thermal energy consumption using a thermal energy consumption ratio of 0.51 (McKenna & Norman, 2010). Apply heat recovery ratio of 10% (McKenna & Norman, 2010).
	Assumptions	CO2 factors based on BEIS conversion rates (BEIS, 2020). Location dataset provided by SEPA. Apply fuel split, load factor and heat recovery fraction (McKenna & Norman, 2010).
Laundry	Approach	Heat extraction: Flue gas The total fuel consumption was estimated based on an average laundry process capacity (20 to 40 tonnes of laundry per day). Apply 0.8 fuel to heat efficiency ratio and 10% heat recovery fraction (this is aligned with other industrial processes).
	Assumptions	Location dataset was obtained from SAA. Fuel consumption: 1529 kWh/tonne (Carbon Trust, 2011)
Data centres	Approach	Heat Extraction: Refrigerant to water The gross floor area of each data centre was estimated using Google maps or using information provided on company websites. Calculate site specific annual cooling load: • For data centres with a floor area less than 2000m^2 – apply a cooling load of 1500 W/m^2 • For data centres with a floor area more than 2000m^2 - apply a cooling load of 600 W/m^2 Apply the load factor and a 30% heat recovery ratio to estimate the waste heat potential.
	Assumptions	Cooling benchmark of 1500 W/m^2 (BSRIA, 2011). Heat recovery ratio of 20% (Carbon Trust, 2020). 1100 annual chiller hours - based on a recent study (Acton, et al., 2018) Apply a load factor of 0.6 to estimate the annual cooling energy consumption.

[10] https://www.whiskyinvestdirect.com/about-whisky/malt-whisky-distilleries-in-scotland

Supermarkets	Approach	Heat Extraction: Refrigerant to water The gross floor area of 11 different supermarkets was estimated using Google maps and calculate the average rated value per m^2 using the rated value dataset. The floor area of 421 supermarkets was estimated using the average rated value per m^2. The site-specific annual electricity and cooling consumption was estimated based on estimated gross floor area. Estimate the heat rejection and apply a 30% heat recovery ratio.
	Assumptions	Location dataset provided by SAA. Heat recovery ratio was based on Carbon Trust Heat Recovery guidelines. Electricity consumption rate of 329 kWh/m^2 (Kolokotroni, Mylona, Evans, Foster, & Liddiard, 2019). Assumed that refrigeration accounts for 50% of total electricity consumption. COP was based on the information provided by IEA (2017). Supermarkets with a floor area smaller than 750m^2 were not included in the assessment.
Waste-water treatment works	Approach	Heat Extraction: Water to water The waste heat potential was estimated using a site-specific average effluent rate. Annual effluent temperature of 5 sites were assessed and the mean temperature was estimated to be 12.3^oC.
	Assumptions	WWTP flow rate and temperature datasets provided by Scottish Water. Apply a fixed delta T (heat extraction rate), using a minimum 4^oC return temperature. Specific heat capacity of waste water: 1.16 kWh/m^3K (Neugebauer, et al., 2015)
Sewer networks	Approach	Heat Extraction: Water to water To be confirmed.
	Assumptions	Apply a fixed delta T (heat extraction rate), using minimum 2^oC return temperature and a conventional water-to-water heat pump system.
Electricity sub-stations	Approach	Heat Extraction: Oil to water Focussed on grid supply points with a minimum capacity of 133/11 kV. Apply a heat recovery ratio of 1% of peak load and a load factor of 0.4. Estimate the waste heat potential using a standard temperature of 45^oC.
	Assumptions	Apply a heat recovery ratio of 1% peak load. Electricity substation data was available on SSEN's website. Heat recovery ratio and load factor assumptions were based on a study carried out by GLA (2015).

Inactive landfills	Approach	Heat Extraction: Water to water (ground-source) Estimate the waste heat potential considering a standard ground source heat pump system with a peak capacity of 73 kW.
	Assumptions	Heat Extraction: Ground source heat pump An average ground temperature of 21ºC (Grillo, 2014). 73 kW of heat pump capacity applied to all the non-operational landfills.

Appendix D: Limitations

Sector	Source of Waste Heat	Limitations
Industrial Processes	Manufacture of Food Products - Bakeries	Due to lack of information on food manufacturing sites, we only assessed the waste heat potential of bakeries by using a set of assumptions. Further research is required to understand heat recovery options suitable for bakeries.
	Breweries	Heat recovery potential of breweries was calculated using an estimated production capacity due to lack of data available. An average thermal energy consumption rate of 41 kWh/bbl was taken into consideration. However, small and medium size breweries might consume more energy than large scale breweries because their smaller volumes do not offset the base energy required to brew a barrel of beer (Brewers Association) Further research is required to understand heat recovery options suitable for breweries.
	Distilleries	An average thermal energy consumption rate of 6.6 kWh/lpa was taken into consideration. However, small and medium size distilleries might consume more energy than large scale distilleries as large-scale distilleries might have heat recovery and energy efficiency measures in place.
	Paper and Paper products	Same fuel split ratio applies to all the sites due to lack of info on actual processes. Paper and pulp mills location dataset only includes the large-scale paper and pulp production sites (TBC)
	Laundry	Limited information available on site-based production capacity and energy consumption. An average laundry capacity rate of 30 tonnes/day was applied. Air quality related issues should be further investigated, as these might affect the heat recovery potential from flue gas. Small laundries and laundrettes were not included in the assessment. Heat recovery from grey water has not been factored in to ‘Laundry’ sites, but rather is dealt with via ‘sewers’.
Commercial	Data centres	Data centre location data set and floor areas were not validated by stakeholders. Heat recovery ratio is only suitable for existing systems. There is a greater potential for heat recovery in new buildings. Seasonal variation was not assessed in detail due to lack of information available on data centre energy consumption and cooling loads. Due to security reasons, some data centres keep their location secret. As a result, only 9 data centres were found in publicly available datasets.
	Supermarkets	Viability of medium-grade heat recovery from supermarkets was not assessed. At large superstores, 10% of potential heat can be high

		grade. However, the recovery of high-grade heat from centralised refrigeration systems is technically complex and require further research. Heat recovery of small cooling/refrigerant systems (<30 kW) may not be a viable solution.
Waste Water	Waste-water treatment plants	Heat recovery potential was estimated using a mean effluent temperature of 12.3ºC. The relationship between flow velocity and heat extraction is not assessed in detail. High effluent velocity might cause technical challenges when recovering heat from waste-water treatment plants. Chemical composition of effluent water and its potential impact on heat pump systems should be further investigated.
	Sewer networks	Not assessed due to lack of information available.
Electricity	Electricity sub-stations	Physical constraints of heat recovery and seasonal variation should be further investigated. Previous research carried out by Imperial College London shows that Oil Forced Water Forced (OFWF) transformers currently offer the most opportunity for heat recovery. However, transformer types were not reviewed or analysed in this study due to limited information being publicly available.
Landfill	Inactive landfills	The ground temperature was assumed to be 21ºC throughout the year due to lack of data on ground temperature and conditions in inactive landfills. Physical constraints and site-specific characteristics should be further investigated.